THE IMPORTANCE OF THE SACRAMENTO-SAN JOAQUIN ESTUARY AS A NURSERY AREA OF YOUNG CHINOOK SALMON, STRIPED BASS, AND OTHER FISHES

BY

THOMAS C. CANNON

ENVIROSPHERE COMPANY
130 Newport Center Drive
Newport Beach, California 92660

FOR

U. S. Department of Commerce
National Marine Fisheries Service
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ABSTRACT

The Sacramento-San Joaquin Estuary provides unique habitat for young of marine and anadromous fishes. The estuary is an important nursery area for many of these fishes including chinook salmon and striped bass. The estuary provides a high food supply, good temperature for growth, and shallow low-velocity habitat, all of which are important elements in young fish survival.

Young salmon depend on high winter flow to support their downstream migration to the estuary where temperature and food supply are optimal. The estuary provides the conditions for young salmon to grow large enough before they are forced to move to the ocean because of high summer water temperatures in the rivers and estuary.

For striped bass, the estuary is an important spawning, nursery, and feeding area. The physical, chemical, and biological processes in the estuary control the population dynamics of the striped bass. Of all the fishes in the Sacramento-San Joaquin system the striped bass is probably most dependent on the estuary. Temperature and food supply are key factors in the survival of young striped bass. Freshwater inflow and water diversions play a key role in controlling temperature and food supply. Freshwater inflow sufficient to maintain the entrapment zone (freshwater-saltwater mixing zone) in the shallow lower area of the estuary produces the greatest abundance of phytoplankton and zooplankton in the estuary. Such high food concentrations are necessary for good survival of young bass. The shallow low velocity and high turbidity habitat of the bays and tidal channels of the estuary is optimal for feeding and rearing of young striped bass. Adequate freshwater inflow to the estuary provides more of this habitat by dispersing young bass into and maintaining them in the shallow bays.

Other fishes which use the estuary 27/28 as a nursery area are the Pacific 42 herring, 1 American shad, anchovy, sturgeon, 25/26 smelt, rockfish, starry 32 flounder, and English sole. These species have adapted as have the salmon and striped bass to the highly productive, protective habitat of the estuary.

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The unique characteristics of the estuary, with its freshwater inflow and freshwater-saltwater mixing zone, provide important habitat as well for many invertebrate organisms such as zooplankton, shrimp, and crabs, all of which provide the food supply for the young fishes. The estuary acts to trap river-born and tidal input ocean nutrients as well as eggs and larvae of fishes and invertebrates, thus providing a unique food-rich habitat.

Freshwater inflow to the estuary, which controls the distribution, growth, survival, and production of young fish and their invertebrate food supply is the most important factor controlling the capacity of the estuary to produce young fish. Declines in the populations of salmon and striped bass over the past 40 years are related, in part, to changes that have occurred in flow patterns to the estuary. Reductions in freshwater inflow from upstream and within estuary water developments have probably played a key role in the declines. The potential impacts of further development could be minimized by improved water management. A prerequisite of such improvement is a clear understanding of the ecology of the estuary. Such understanding is presently incomplete.

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I. INTRODUCTION

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I. INTRODUCTION

The Sacramento - San Joaquin Estuary is a spawning, nursery, and migratory route for many fish species including chinook salmon, striped bass, American shad, white sturgeon, smelt, Pacific herring, and northern anchovy, many of which are dependent on the estuary during key portions of their life cycles. The estuary especially provides the necessary physical-chemical conditions, high food supply, and habitat for their young.

The extent to which these fishes depend upon the estuary is the primary topic of this report. The considerable information available on this and other estuaries provide a basis for evaluating the extent and degree of dependence.

Even though the estuary has been studied extensively, much about the ecology of the estuary is still unknown; therefore, many of the statements and conclusions presented in this report are theory based on limited facts.

The chinook salmon, discussed in Section II, is emphasized because it has important commercial and recreational fisheries and because its environmental needs in the estuary are not well understood (California State Water Resources Control Board 1978). Available evidence indicates that the estuary has been and is now an important element in the life history of the chinook salmon and that wild elements of the stock as well as the hatchery element depend on conditions in the estuary for good survival and recruitment. The information and analysis presented should aid in identifying environmental factors in the estuary which should be managed to protect the salmon resource.

The striped bass, discussed in Section III, is also treated in detail because of its important recreational fishery and because present water quality standards in the estuary are based in part on striped bass environmental requirements (see California State Water Resources Control Board 1978). Sharp unexpected declines in the striped bass population over the past four years indicate a need for better understanding of striped bass environmental requirements (see California Department of Fish and Game 1981 and National Marine Fisheries Service 1981).

Other species of fish are discussed in Section IV in less detail because little information is available on these lesser known species. Although environmental requirements are similar for many of these species, differences are sufficient to require separate analyses if populations are to be adequately protected. Such analyses can only be performed after sufficient information is collected.

Various abundant invertebrates, important as prey of fishes in the estuary, are discussed in Section V. Since man's activities may affect fish indirectly through the invertebrate food supply, review and analyses of the environmental requirements of these organisms may help provide a more direct resource management strategy for the estuary.

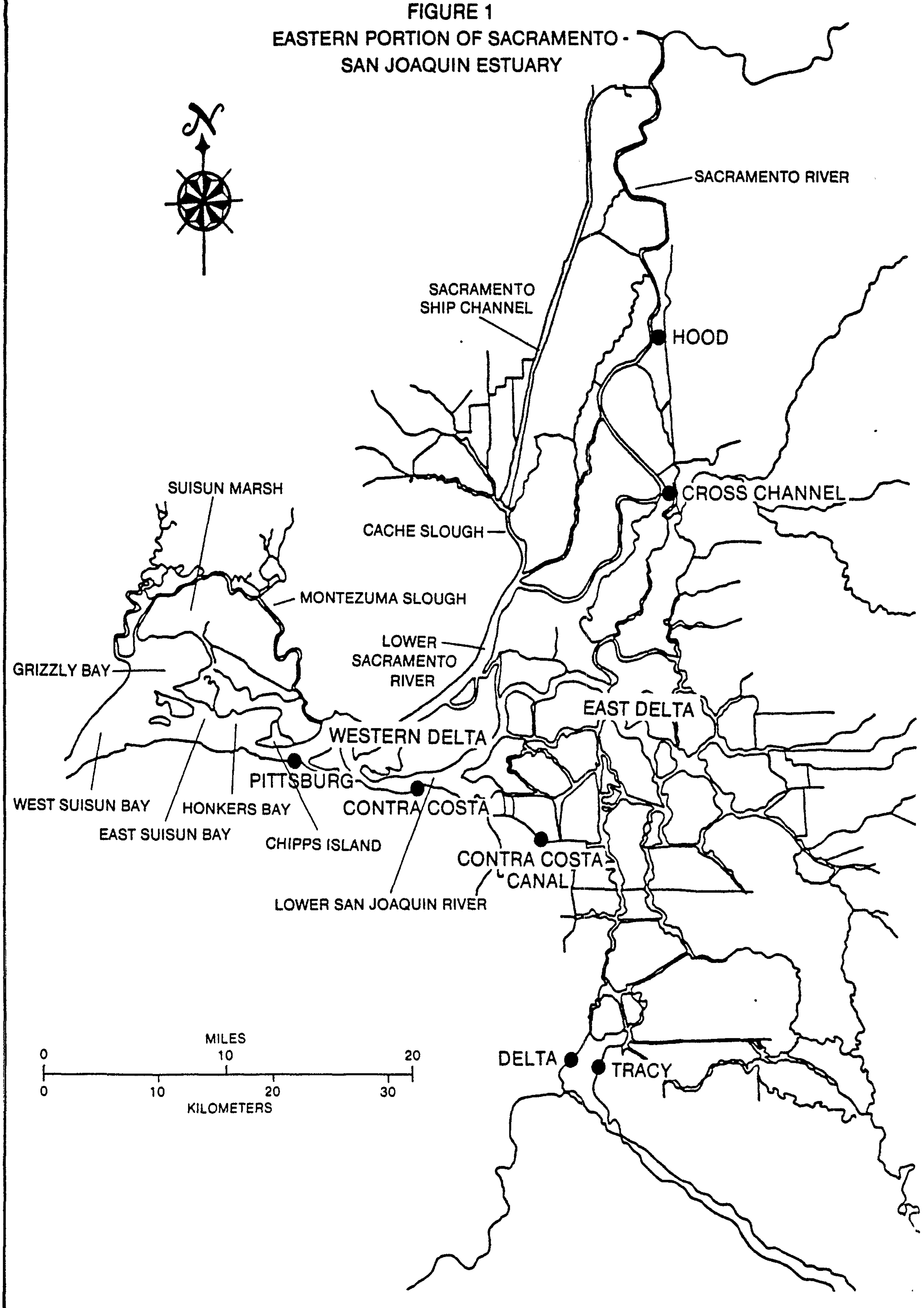
Energy sources for the estuary, discussed in Section VI, represent the foundation for biological productivity in the system and thus relate directly through the food chain to the production of fish.

Sacramento - San Joaquin Estuary

The Sacramento - San Joaquin Bay-Delta, one of the largest estuarine systems on the Pacific Coast of North America, includes San Francisco Bay, San Pablo Bay, Suisun Bay, and the Sacramento-San Joaquin River Delta. Most of this discussion focuses on the eastern estuary including Suisun Bay and the Delta (Figure 1), which contains the principal location of young chinook salmon and striped bass, and the freshwater-saltwater mixing zone of the estuary.

South and Central San Francisco Bay are very important especially to marine fish which use the Bay/Delta estuary; however, since very little is known about the lower bays as yet, they and their fish fauna are not discussed in detail. San Pablo Bay located between Suisun Bay and Central San Francisco Bay is an important transition zone which during wet years (at least historically) provides important nursery habitat to chinook salmon and striped bass.

FIGURE 1
EASTERN PORTION OF SACRAMENTO - SAN JOAQUIN ESTUARY



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II. CHINOOK SALMON

II. CHINOOK SALMON

The chinook salmon, commonly called king salmon, is the only species of salmon maintaining a significant population in the Sacramento-San Joaquin river system. The Sacramento-San Joaquin population is one of the largest on the Pacific Coast with spawning adults ranging in number from 100,000 to 500,000 annually (Ganssle 1966, Jensen, 1972, Kjelson et al 1981a). The number of adults in the population totals about 1 million fish. Hart (1973) describes the species over its Pacific range while Kjelson et al (1981b) have recently described the life history of juvenile chinook salmon in the Sacramento-San Joaquin estuary.

Chinook salmon are anadromous; they spend much of their lives in the ocean before migrating to freshwater rivers and streams to spawn. Young hatch in the stream gravel and eventually migrate to the ocean during their first or second year where they spend one to five years before returning to their natal rivers to spawn.

The early life history of chinook salmon is probably the most complex of all the Pacific salmon (Healey 1980a). Chinook young rear in a wide variety of habitats from rivers to the ocean. After emerging from the gravel, they may remain in freshwater or move directly to the river, delta-estuaries or the sea. In their southern range (California to British Columbia), chinook generally migrate to the ocean during their first year, although in some of the larger and longer rivers, such as the Fraser, Columbia, and Sacramento-San Joaquin, subpopulations remain in the upper rivers until their second year (Mason 1964 and Healey 1980a). In their northern range, northern Canada and Alaska, the young may remain in rivers two or more years.

Within a river system there may be one or more distinct races of chinook salmon distinguished by the season of the year in which the adults migrate into the rivers. The two most common races or sub-populations are the fall and spring "run" chinook. Summer and winter runs are less common types. Spring, fall, late-fall, and winter runs have been identified in the Sacramento-San Joaquin system. The different runs often have distinctly different life history patterns within the same river system.

Of the five major species of Pacific salmon, the chinook appears to utilize estuaries of their natal rivers most extensively. Sockeye salmon rear in streams and lakes before migrating to the open ocean. Chum and pink salmon migrate quickly to the ocean after hatching. Coho salmon usually remain one or more years in rivers and streams before migrating to the ocean.

Estuaries are an important transition zone for all of the Pacific salmon because of the change from the freshwater to saltwater environment. Young salmon must undergo physiological changes to minimize the stress from transition to seawater which has salt concentrations higher than their body fluids.

For chinook salmon, estuaries also are an important nursery area where young may spend from weeks to months growing through critical early stages before migrating to the ocean. The period of estuarine residence and the mechanisms by which they reach the estuary may be critical elements in their overall survival.

Downstream Migration of Young

Most chinook salmon characteristically spawn in the fall or winter. After an incubation period of several months (varies with the incubation temperature), the eggs hatch and the fry gradually emerge from the gravel. After emergence, fry may establish territories in the stream or migrate downstream to the lower river, estuary, or ocean. This migration may occur immediately or later during their first or even their second year of life.

Most of the young chinook salmon in the Sacramento-San Joaquin system migrate downstream in winter and early spring. Some reach the Bay/Delta estuary as fry (30-50 mm) during the winter, others reach the estuary as fingerlings (50-70 mm) or subyearling smolts (70-100+ mm) in the spring after spending some time growing in rivers before reaching the estuary (Jensen 1972, Kjelson et al 1981a). Hatchery-reared subyearling smolts contribute substantially to the spring subyearling migration (Hallock 1978). Some subyearling winter run young spawned in the upper Sacramento River in the summer migrate downstream in the fall along with a small number of yearling fall and spring chinook which had remained in the upper river for their entire first year (Kjelson et al 1981b).

The timing and degree of the migration depends on the freshwater flow pattern in the system. When winter flows are high (20 to 40 thousand cfs or above), large numbers of fry are distributed into the estuary; at low flows (less than 10,000 cfs), few fry reach the estuary (see Erkkila et al 1950 and Kjelson et al 1981b). Fingerlings and subyearling smolts reach the estuary during the spring with peak migration in May and June (Ganssle 1966, Jensen 1972, Kjelson et al 1981b). Historically, young salmon migrated downstream into the Delta during February, March, and early April when flows were high and left the Delta for the lower estuary by May (Erkkila et al 195), Ruttner 1903, and Hatton, 1940).

There is some debate on whether fry that reach the estuary actually migrate or are washed downstream at high flows, and whether they are subsequently able to survive. However, research from the Columbia River system and the Sacramento River indicates that high turbidity associated with high flows actually stimulates young to migrate (Gauley et al 1958, French and Wahle 1959, and T. Richardson, U. S. Fish and Wildlife Service, personal communication). During high flows, fry move to the high-velocity center portion of the river, while at low flows, they remain near shore in protective habitat (Mains and Smith 1964).

Fry probably have adapted to migrate during the high-flow high turbidity periods to minimize predation. In years with moderate high winter flow, fry reach the estuary quickly and predation by predators living in the Sacramento river in great numbers is minimized. In low flow years, some or all the fry remain in rivers where predators, over-crowded conditions, and poor food supply probably results in high mortality.

Estuarine Residence

As the young salmon reach estuaries, their migration rate decreases and their feeding increases with the increased food supply (McDonald 1960, Dunford 1975, and Healey 1978). In many estuaries, young encounter shallow productive marsh, tidal flat and channel, slough, or bay habitats. Abundant crustacean food supply and the relative security of shallow turbid water with cover provide good rearing habitat. The delta and bays of the Sacramento-San Joaquin Estuary provide such habitat in winter and spring. Young chinook reside in late winter and spring in similar habitat in Pacific Northwest estuaries (Congleton and Smith 1976, Dunford 1975, Healey 1978, Levy et al 1979, Durkin et al 1979, and Reimers 1973).

From late spring through summer, young move to lower estuaries and adjacent marine waters where they may spend most of their first and even part of their second year (Dawley et al 1980, Fresh et al 1978, Healey 1978 and 1979, Schreiner et al 1977, Sibert 1975). The late spring-summer habitat of young salmon in the Sacramento-San Joaquin Estuary is not known; however, young salmon are likely to be found in San Francisco Bay (at least through early summer) and nearby coastal waters based on the experience in Pacific Northwest estuaries cited above. Rutter (1902) cited the observation of yearling salmon in San Francisco Bay.

Estimates of residence time in estuaries for individual young range from weeks to months. Shorter periods are for downstream migrant yearlings (Dawley et al 1979 and 1980) and longer periods for fry (Dunford 1975, Healey 1978 and 1979, and Sibert 1975). Residence time of fry in the Sacramento-San Joaquin Delta is as long as 50 to 60 days; residence time of smolts in the Delta is up to 10 to 17 days (Kjelson et al 1981b).

Residence period likely varies depending on initial size in estuary. Smaller fish tend to reside longer indicating a threshold emigration size may exist. Young probably do not leave estuaries for the ocean until they reach about 100 mm or more. Young less than 100 mm are seldom found in marine waters of Oregon, Washington, and British Columbia (Dawley et al 1979, Dunford 1975, Hartt 1980, Reimers 1973, Schlucter and Lichatowich 1977, and

Healey 1978 and 1980a). At 100 mm, most young have produced gill ATPase, a chemical for reducing osmotic stress of transferring to sea water from freshwater (Ewing et al 1977). In some cases, young may migrate to cooler marine waters at a smaller size if water temperatures in estuary are above 15C (Dunford 1975, Healey 1980b); such high temperatures may occur in the Sacramento-San Joaquin Delta as early as May (see Conomos et al 1979).

During their residence in the estuary, young salmon put on the important growth because, for many salmon populations, the size of young migrating to sea is directly related to subsequent abundance of adults (Ricker 1976, Parker 1971, Foerster 1968, Matthews and Buckley 1976, and Meyer 1979). Larger young are also better adapted to seawater and more able to feed effectively and avoid predators (Parker 1971, and Clark, Shelbourn, and Brett 1978). Typical growth rates in estuaries are in the range of 0.5 mm to 1.5 mm per day (Healey 1978 and 1980b, Sibert 1975, and Kjelson et al 1981b). Growth of young in the estuary from 40 mm to 100 mm represents a weight increase from about 0.5 grams to 10 grams (a twenty fold increase) before migrating to sea. For smolts rearing from 70-80 mm to 100 mm, weight doubles (5 grams to 10 grams).

Available evidence indicates estuarine rearing does result in higher total survival. Variability in first year survival in many river systems is related to conditions occurring during estuarine residence (Schreiner 1977, Reimers 1973 and 1977, Diamond and Pribble 1978, and Meyer 1979). Kjelson et al (1981) found survival of young salmon released in Suisun Bay was much greater than survival of young released in the Delta or upstream in rivers.

Survival of salmon is higher in estuaries because estuaries provide better habitat for young salmon. Water temperature warms to optimum growth range (12-14C, Brett 1952) earlier than rivers or ocean. Optimal temperatures occur in shallows of the Sacramento-San Joaquin Estuary by February in most years (see Conomos et al 1979). Temperatures in lower estuary and adjacent marine water remain optimal in summer after upper estuary and rivers reach intolerable levels (18-20C, Healey 1980b). In the Sacramento-San Joaquin Estuary, higher survival in lower bays of tagged hatchery fish may be due to less predation and water diversion than occurs in the upper estuary (Kjelson, et al 1981b).

Food supply also is greater in the estuary. The principal prey of salmon young (copepods, cladocerans, amphipods, chironomids, and mysids (Levy et al 1979, Craddock et al 1976, Congleton and Smith 1976, and Kjelson et al M.S.) are very abundant in estuaries (Arthur and Ball 1979, Simenstad et al 1981).

Estuaries also tend to have few effective predators (Simenstad et al 1981). High turbidity provides protection from predators. Extensive shallows and shorelines also provide abundant cover. Salmon fry and fingerlings feed heavily on crustaceans in this shallow habitat especially at night (Meyers et al 1979) and slack tides when current velocities are minimal (Bailey et al 1975, Congleton and Smith 1976).

Young chinook salmon reared in the estuary may have a growth advantage over river-reared young. Under optimal temperature and food supply, fry reaching the estuary by February or March should increase to ocean size (100 mm or greater) by April and May (assuming a growth rate of 1 mm per day). Fingerlings and subyearling smolts reared in the rivers before migrating to the estuary in April and May (Kjelson et al 1981b) would probably reach 100-mm smolt size in May and June. Hatchery reared subyearling smolts released in the estuary in May and June at 70-80 mm in length should reach ocean size within one month. If estuary reared fry grow faster, they would probably migrate to the ocean before river reared young. In British Columbia, fry reared in the Nanaimo River estuary grow faster and are the first to migrate to sea (Healey 1980a).

Early migration to the lower estuary and ocean may be a selective advantage in the Sacramento-San Joaquin system because high water temperatures in the upper estuary are generally less than optimal for good growth (12-14C, Brett 1952) by April-May and near avoidance level (18 to 20C, Healey 1980b) by May-June. In addition, food supplies may be greater and competition from striped bass young less before June in the upper estuary. Delta outflow is also reduced in May-June from April and possibly makes outmigration more difficult. Pacific herring and smelt young, a major prey of chinook salmon smolts (Healey 1978, Simenstad 1977 and 1979, Fresh et al 1978, and Lipovsky 1977), are more abundant in late winter-spring period (Ganssle 1966, Messersmith 1966, and Pacific Gas and Electric Company unpublished data).

Factors Limiting Growth and Survival of Young Salmon

Important factors which limit growth and potential survival of young salmon during their period of estuarine residence are water temperature, food supply, freshwater inflow, predators, competitors, and water diversions.

Water Temperature

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The optimal temperature for growth of young chinook salmon is 12-14C (Brett 1952). Temperatures below or above the optimum range limit growth rate. Conditions for optimum growth of young salmon in the estuary occur when the estuary warms early and remains in the optimal temperature range through the spring.

Early growth of young salmon is probably highest in the bays of the Sacramento-San Joaquin Estuary because bays warm first. In the shallow bays of the estuary, San Pablo Bay and Suisun Bay, water generally warms to 12C in February. In the Delta, water temperature does not generally reach 12C until March. (Pacific Gas and Electric Company unpublished data and Conomos et al 1979).

High temperatures in the spring may inhibit growth in the shallow bays of the estuary. Water temperature in the spring increases to 15C and above especially in Suisun Bay and the western Delta where water temperature rises rapidly to reach 15C as early as March in warm years (1968, 1972, 1976, 1977 and 1978) (PG and E unpublished data). Temperatures are usually above optimal in Suisun Bay and the western Delta by April except in cold wet springs (1967, 1971, 1974, and 1975) when temperatures do not exceed 15C until late April. In San Pablo Bay, temperatures do not exceed 15C until May. Temperatures in San Francisco Bay do not exceed 15C until summer (see Conomos et al 1979).

Water temperature increases to 15C and above in March through May period in upper estuary may induce early migration of young salmon to the lower estuary or sea. Young are known to migrate to sea in some estuaries as water temperatures reach 15C (Dunford 1975 and Reimers 1973). Water temperatures in excess of 18C, which occur in the upper estuary by May or June, would inhibit residence in the upper estuary based on studies by Healey (1980b). Temperatures in San Pablo Bay exceed 18C beginning in June of warm years. Temperatures rarely exceed 18C even during the summer in Central San Francisco Bay (see Conomos et al 1979). Early warming in Suisun Bay, Delta and lower Sacramento River may block river-reared fingerling and smolt migration or greatly increase their mortality during migration and residence. High spring temperatures in the upper estuary may also explain the rapid migration of smolts through the upper estuary during May and June noted by Jensen (1972) and Kjelson et al (1981b). Erkkila et al (1950) state that water temperature is an important factor in regulating the exodus of young salmon from the Delta.

Food Supply

The principal food of young salmon are crustaceans and insects. Fry feed on chironomids, amphipods, copepods, and cladocerans in upper freshwater portions of estuaries (Congleton and Smith 1976, Levy et al 1979, and Kjelson et al 1981b), and mysids and amphipods in lower brackish water portions of estuaries (Healey 1980b). Fingerlings and smolts feed on much the same prey (Craddock et al 1979, Lipovsky 1977, Durkin et al 1979, and Kjelson et al M.S.) except they generally prefer larger prey. The crustaceans, Corophium and Neomysis, and Pacific herring and smelt larvae are preferred food of smolts in estuaries and adjacent marine waters (Simenstad et al 1977 and 1979, Healey 1978 and 1980a, Lipovsky 1977, and Fresh et al 1978). Smolts feed heavily on fry if available (Levy et al 1979).

Important factors which regulate the distribution and abundance of these organisms are freshwater flow, coastal upwellings, water temperature, current velocities, bottom type, and their food supply (see Sections IV-VI for more detail). How these factors control abundance and distribution of the key prey organisms or the indirect effect on young salmon growth and survival are not well understood. Flows and temperatures necessary to maximize production of key invertebrate food items of young salmon in different regions of the estuary and at different times are not known.

Freshwater Flow

Freshwater inflow to the estuary directly affects salmon migration, water temperature and food production and thus indirectly affects growth and survival. High flows in the winter and spring are the means by which young are able to actively migrate from spawning rivers to the more productive habitat of the estuary. High freshwater flows also stimulate and sustain production of food.

Sacramento River flows in excess of 20,000 cfs in the winter appear necessary to get fry to the estuary from the Sacramento River system (see Erkkila et al 1950 and Kjelson et al 1981). Sustained flows under 20,000 cfs would probably result in delayed migration of fry to the estuary. Sustained flows under 10,000 cfs, as occurred in 1977, would result in few fry reaching the estuary. Flows in excess of 40,000 cfs may be necessary to get fry to historical nursery areas in San Pablo anbd Central San Francisco Bays.

Predators

Based on trawling and gill net surveys by Fish and Game in San Pablo and Suisun Bays (Ganssle 1966 and Messersmith 1966), the only abundant piscivorous fish predator was striped bass. Sacramento squawfish, a significant predator of young salmon in the Sacramento River (including the North Delta), are rare in the bays. Extensive food habit studies of the striped bass (Ganssle 1966) indicate salmon young may be a minor component of the diet of striped bass during the late winter and early spring period of migration into the Bay-Delta. Herring, anchovy, and smelt young were about 200 times more abundant than young salmon at this time, thus predation on salmon is probably minimal. Other marine piscivorous fish such as the lingcod and California halibut were rare in the bays.

In the Delta, both striped bass and Sacramento squawfish are abundant piscivorous predators. Studies of Fish and Game (Farley 1966) and Pacific Gas and Electric Company (Ecological Analysts 1981a and 1981b) indicate striped bass and squawfish are common in the Delta during late winter and spring when young salmon are abundant. Smelt young were also common;

however, anchovy and herring young were rare. Based on these limited data, predation pressure on young salmon is likely greater in the Delta than in the bays. Higher survival of hatchery-reared salmon in Suisun Bay compared to the Delta (Kjelson et al 1981b), may be partly due to a lower predation pressure in Suisun Bay.

Competitors

During the winter and early spring period when fry rear in the estuary, competition occurs with other fishes and invertebrates for food and space. The young of many marine fish migrate into the estuary to also take advantage of the abundant food supply. The effect of competition would depend on the degree of habitat and food overlap between species and the abundance and productivity of the common food source. Competition is likely to be more severe when food supplies are low.

Water Diversions

Estimates of annual losses of young salmon at the delta pumping plants range from 50,000 to 300,000 per year (CDF&G et al 1978). These estimates may be underestimated by a factor of 20, based on results of recent studies (Hall 1980) which indicate a potentially high rate of predation near the intakes of the State Pumping Plant. The National Marine Fisheries Service (1981) estimates annual losses of young salmon as high as 6 million after corrections for predation losses are included. The Red Bluff Diversion Dam on the upper Sacramento River may also have a significant effect on downstream migrants salmon (Reisenbichler M.S. and USF&WS 1981).

SUMMARY AND CONCLUSIONS

Importance of Estuary to Chinook Salmon

Research on populations of chinook salmon in California, Oregon, Washington, and British Columbia indicates estuaries are important to the production of young salmon. Both the abundance and size of young upon entering the ocean are directly related to the subsequent numbers of adults in the population. Survival and size are determined through the growth process which in turn is controlled by food supply, temperature, and habitat. The Sacramento-San Joaquin Estuary provides good habitat for growth and survival because temperatures are near optimal for growth and invertebrate prey are extremely abundant during the winter-spring rearing period. The shallow, low velocity, high turbidity habitat in the estuary is optimal for young salmon and their food supply. Fry rearing in the estuary put on 95% of their total weight during their estuarine rearing period. Smolt salmon which reach the estuary in the spring and reside only a few weeks before migrating to sea may still double their weight during their estuarine residence. High growth rates get young into larger sizes quicker where they are better able to avoid predators, capture prey, and withstand the physiological stresses of the environment. Young salmon reared in the estuary probably grow faster and migrate to the ocean sooner than those reared in the rivers.

Importance of Freshwater Flow

For chinook salmon, river flow is the mechanism which gets newly hatched salmon to the more optimum habitat of the estuary and away from predators like squawfish which are abundant in rivers and Delta. High flows provide the turbidity necessary for young salmon to migrate and avoid predators. In addition, basic nutrients from the high flows may stimulate late-winter and spring blooms of algae and invertebrates in the bays that provide the food chain for young salmon.

III. STRIPED BASS

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III. STRIPED BASS

Striped bass were introduced toward the end of the last century from Hudson River stock on the east coast. They adapted well to the conditions in the estuary and are an important sportfish and top carnivore in the system. The population has declined gradually over the past 40 years with a more serious decline over the past five years. The population has declined from about 4-million adults in the 1960's to about 1-million adults in 1980 (D. Stevens, personal communication).

Striped bass are anadromous, spending much of their adult lives in marine bays and coastal waters and migrating to freshwater portions of estuaries and rivers to spawn. Eggs are spawned and hatched in freshwater, young are carried by currents to low velocity mixing zones of the estuary where they develop and grow during the first and second years. Striped bass often return to the estuary and natal rivers in their next few years to feed, before returning as mature fish at 4 to 6 years of age. Striped bass do not die after spawning as salmon do; many return to the ocean, bays, and estuary.

Estuaries are important spawning, nursery, and feeding area for striped bass. Physical, chemical, and biological processes in the estuaries control the population dynamics of the striped bass. Recruitment and production are functions of estuarine conditions. Of all the fishes in the Sacramento-San Joaquin system, the striped bass is probably most dependent on the estuary, being especially adapted to the complex variable conditions of the estuary.

Distribution of Young in Estuary

Although striped bass spawn in much of the freshwater portion of the Sacramento-San Joaquin Estuary, most of the spawning occurs in the mid-Sacramento River and lower San Joaquin River (Turner 1972 and California Department of Fish and Game et al 1976). Spawning occurs in the spring at 15 to 18C. Because the San Joaquin warms earliest, spawning starts there usually in late April and continues into the Sacramento in June during cooler high flow years. Generally, San Joaquin eggs hatch and larvae develop where they were spawned; however, in the Sacramento which has much higher flows, eggs and newly hatched larvae are washed downstream quickly to the Delta. Most reach the Delta as early larvae (4-6 mm) in mid to late May within 10 days of spawning (CDF&G et al 1974, PG&E unpublished data). Peak movement of the small larvae out of the mid-Sacramento River into the western Delta generally occurs during a two-week span in mid to late May (DFG 1976, PG&E unpublished data). In cold, wet years (i.e., 1967), peak movement may occur as late as June. There is no evidence to indicate that river flow affects the abundance of larval reaching the Delta from the Sacramento River.

Larvae (young 4 to 16 mm in length) accumulate in the western Delta (Chipps Island to Sherman Island and lower portions of Sacramento and San Joaquin Rivers), or Suisun Bay (see Figure 1) depending on river inflow. In 1978, at high flow rates (20 to 40 thousand cfs Delta Outflow Index) from mid May to early June, larvae were most abundant in the area of Suisun Bay (including Grizzly Bay, west and east Suisun Bay channels, Honker Bay, and Montezuma Slough) and the western Delta (PG&E unpublished data). Larvae were also abundant in the Sacramento Ship Channel and Cache Slough area. Due to the high flows, some larvae were found in San Pablo Bay and even south and central San Francisco Bay. In 1979, at lower flow rates (10 to 20 thousand cfs Delta Outflow Index) from mid May to early June, larvae were concentrated further east, but were still abundant in Grizzly Bay, Montezuma Slough, eastern Suisun Bay, Honker Bay and the western Delta (PG&E unpublished data).

Surveys of striped bass eggs and larvae performed by California Department of Fish and Game from 1967 to 1977 (excluding 1974) indicate that in wet years (1967 and 1969) larvae were most abundant (70 to 90 percent) in west Suisun Bay (see Appendix A and B). In dry years (1968, 1972, 1976, and 1977), most of the larvae (greater than 90 percent) were in the Delta. In years when flows were below normal (1970 and 1973), larvae were again still more concentrated in the Delta but were also abundant (10 to 30 percent) in east Suisun Bay. For normal and above normal flow years (1971 and 1975), larvae were most abundant (more than 60 percent) in east and west Suisun Bay.

Larvae are concentrated in freshwater and the upstream portion of the freshwater-saltwater mixing zone (entrapment zone). A very similar distribution of larvae is evident in the Potomac River on Chesapeake Bay (Setzler-Hamilton et al 1981) and the Hudson River, New York (McFadden et al 1980).

Juvenile striped bass (subyearling 16 to 100 mm) during their first summer, fall, and winter gradually move into more saline waters of the estuary. In June and July of 1978 and 1979, early juveniles (16 to 30 mm) concentrated in the entrapment zone of the estuary (PG&E unpublished data). During early June 1978 when outflow was 10 to 20 thousand cfs, juveniles were most abundant in east Suisun Bay, Grizzly Bay, Montezuma Slough, and Honker Bay. From late June through July as outflow declined to less than 5,000 cfs, juveniles moved (or stayed) with the entrapment into the western Delta. They remained abundant in Montezuma Slough. In June and July of 1979, flows were similar to July 1978 and juvenile bass were again most abundant in the western Delta and Montezuma Slough.

Summer townet surveys performed by CDF&G from 1961 through 1978 (excluding 1966) indicate that in wet summers (average flows greater than 8,000 cfs - 1967, 1969, 1971, 1974, and 1975) most juvenile bass (20 to 50 mm) are in Suisun Bay (Figures 2A and 2B and Appendix C). In dry summers (below 5,000 cfs average - 1961, 1962, 1964, 1968, 1976, and 1977) most juvenile bass are in the Delta. In below-normal to normal summers (average 5,000 to 7,000 cfs - 1963, 1965, 1970, 1972, and 1973), juveniles were abundant in the western Delta and Suisun Bay.

Total abundance is also higher in wetter years than dry years. Abundance indices for below-normal to normal summer flow years (where flows averaged at least 5,000 to 7,000 cfs) were high except for 1972 (the year of the Andrus Island break). Delta outflow of 5,000 to 7,000 cfs is adequate to maintain entrapment zone in Suisun Bay at least during part of the tidal cycle.

Another observation from the summer townet survey data is the decline in abundance of young striped bass in the lower Sacramento River (Figure 2A).

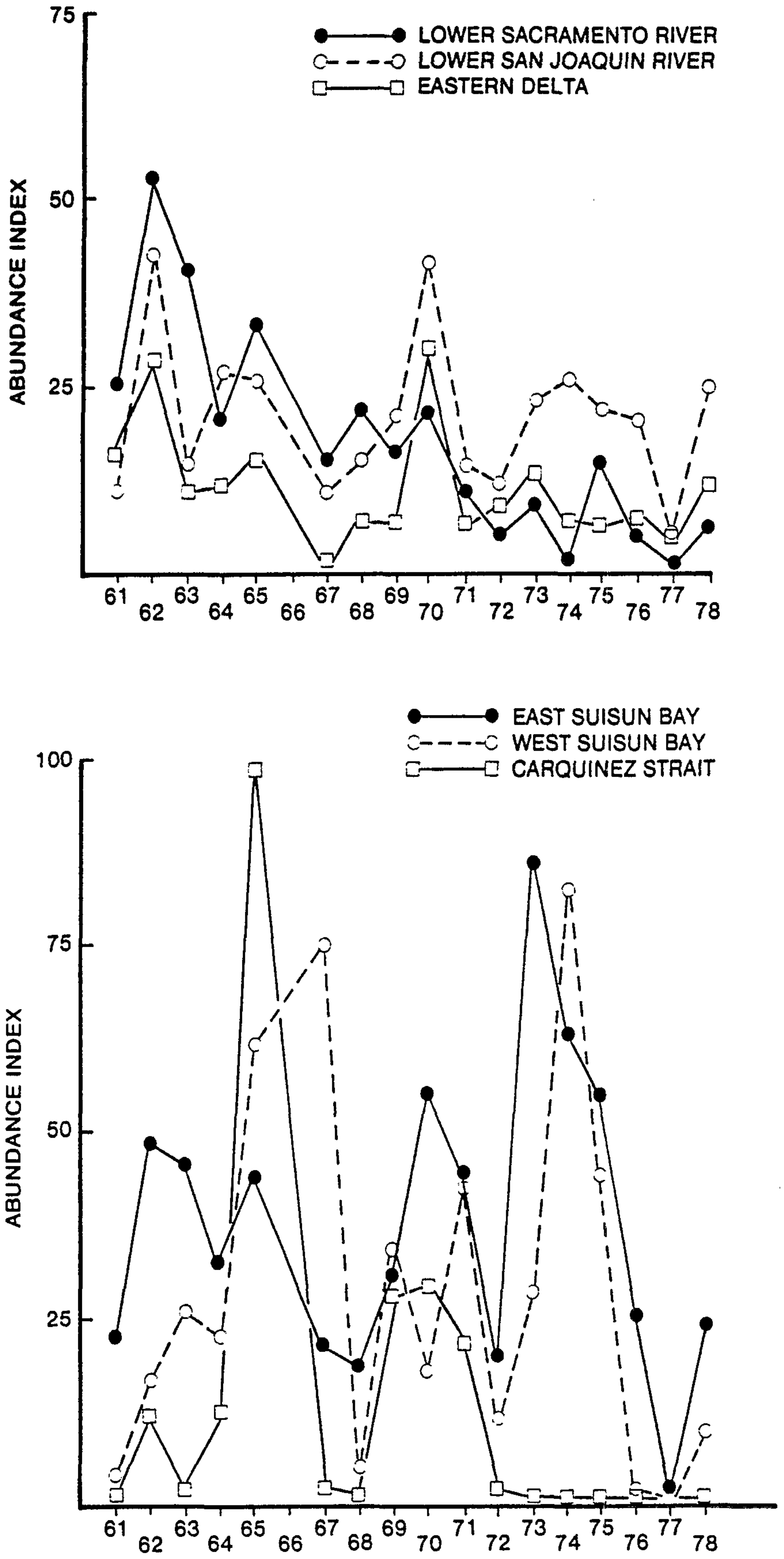

FIGURE 2 (A AND B). DISTRIBUTION OF JUVENILE STRIPED BASS IN SACRAMENTO - SAN JOAQUIN ESTUARY FROM SIX SUBREGIONS AS DERIVED FROM CALIFORNIA DEPARTMENT OF FISH AND GAME SUMMER TOW-NET SURVEY DATA, 1961 TO 1978.

High carriage water flows during the 1970's has apparently reduced the nursery capacity of this area. Capacity in the San Joaquin may have also decreased. High velocities in the Delta channels severely reduce phytoplankton and zooplankton concentrations (J. Arthur, Bureau of Reclamation personal communication and Turner and Chadwick 1972).

From August through November of most years juvenile striped bass are most abundant in the western Delta, Montezuma Slough, and Grizzly and Honkers Bays (Ganssle 1966 and CDF&G fall mid-water trawl survey data). As flows increase in the fall and temperatures decline, young move offshore and downstream. At outflows above 20 thousand cfs, many move to San Pablo Bay. In the dry fall of 1978, when outflow remained around 10,000 cfs or less, young remained in the western Delta and Suisun Bay until January (PG&E unpublished data). Movement to San Pablo Bay in association with increasing flows and increased habitat may increase survival of young bass by increasing available low salinity habitat.

Yearling striped bass concentrate in San Pablo Bay from October to March and in Suisun Bay and the Delta from May to October (Ganssle 1966). Little is known about factors affecting yearling survival.

Growth and Survival of Young in Estuary

Growth of young striped bass is controlled by temperature and food supply. Optimal growth and development for embryonic and newly hatched larval striped bass occurs at 16 to 18 C (Morgan et al 1981). For older larvae and juvenile, optimal growth occurs at 24 to 26C (Cox and Coutant 1981). Growth rate increases from a minimum at 16C and with increasing density of food. Temperature provides the potential for growth while food supply fills the potential (Rogers and Westin 1981). The growth rate of the population depends on the ability of individual groups to find and sustain themselves on dense patches of prey (Eldridge et al 1981).

Eldridge et al (1981) found that growth rate varied greatly with food supplies from 0.1 to 5.0 nauplii of Artemia per ml. Highest growth rate occurred at 5.0 nauplii per ml; about half that rate occurred at 1.0 nauplii per ml. Since young bass in the wild feed on copepodites and adult copepods and larger cladocerans, the density of zooplankton required may be less than in the above lab studies because the larger prey are usually easier to capture and provide a greater amount of energy per individual prey.

Growth measured in the wild conforms to that expected based on lab studies. Dey (1981) in the Hudson River found growth rate was higher in warmer years. The Hudson River generally reaches 20C by mid June and 23 to 25C in July. Faster growth occurs in the Chesapeake where temperatures reach 22 to 24C in May soon after spawning (Setzler-Hamilton et al 1981).

In the Sacramento-San Joaquin Estuary, growth rate and temperature patterns are similar to those of the Hudson River. In 1978, growth accelerated in early June as temperatures reached 20C (PG&E unpublished data). Growth rate was about 0.5 mm per day during June. Actual growth rate of individual young was probably higher because of recruitment of small larvae from upstream and avoidance of the plankton-net gear by larger young.

Growth is a key factor in survival of young bass because the survival rate of young bass generally increases exponentially with size and development. Larger size allows young to feed on larger more diverse prey and to seek out high density patches of prey. In addition, larger size allows young to seek out areas of better protection from predators or to actively avoid predators. Since survival is very much dependent on growth, it is therefore also dependent on water temperature and food supply. Many researchers have suggested that survival is related to food abundance and availability (Turner and Chadwick 1972, Heinle and Flemer 1975, Heinle 1977, Rogers and Weston 1977, Miller 1976 and 1978, Eldridge 1978 and Rogers 1978).

Eldridge et al (1981) related density of zooplankton food in a laboratory study to survival of young bass. They found mortality decreased from 11 percent per day with no food, to 5 percent per day with 0.01 nauplii per ml, to 0.6 percent per day with 5 nauplii per ml. The total survival of the three groups after 30 days is only 3 percent for no food, 22 percent for 0.01 nauplii per ml, and 83 percent for 5 nauplii per ml. These survival rates were determined for larvae reared at 18C; at more optimal temperatures (20 to 24C), these differences are probably even greater.

Eldridge et al (1981) also found that larvae survived starvation well up to 18 days after hatching when the oil globule from the egg was totally absorbed at 18C. Higher temperatures would reduce the duration of this period. This ability to exist on stored food allows the larvae more time to find (actively or passively) dense patches of zooplankton required for good growth. The size at which the oil globule is absorbed (when larvae are about 7 to 8 mm) is the critical stage in which young must find adequate food supplies to survive (Rogers and Weston 1977). This critical stage occurs sooner after hatching in warmer years. Rogers and Weston (1981) point out that larger female bass produce larger eggs with larger oil globules. Larvae from these females probably have greater survival potential than larvae from smaller females.

Temperature controls growth potential and production of food supply (Dey 1981 and Kernehan et al 1981). In the Chesapeake, low winter temperatures have long been associated with strong yearclasses (Kohlenstein 1980). Low winter temperatures cause more discharge of detritus from marshes (possibly by ice scouring) which result in a greater production of zooplankton during the spring (Heinle et al 1977). Warm spring temperatures also result in higher production rates of zooplankton thus greater survival of young bass. Sudden drops in temperature after spawning have caused severe mortality of larvae in the Hudson River (Dey 1981).

Mortality rates of young bass measured from field surveys gradually decline with length and age of larvae. For the Hudson River, Dey (1981) estimated mortality during June (primarily larvae) to be 15 to 18 percent per day; during July (mostly juveniles) mortality was 5 percent per day; and from August to October it was 0.5 percent per day. The high rate in June reflects a less than optimal food supply. The lower rates in the summer and fall reflect the larger size of young which are better able to capture and seek out prey and avoid predators. These rates are similar to the 9 to 10 percent per day for early larvae determined for Sacramento-San Joaquin Estuary larvae from 1968 to 1973 (DFG et al 1974) and the 3 to 8 percent per day for juveniles in summer in the estuary (Turner and Chadwick 1972). Mortality rates decline significantly after the first year. Variability is also very low compared to the variability during the larval period.

Factors Limiting Production of Striped Bass

On the Atlantic Coast, environmental factors limiting the survival of young appear to control production despite very high harvest rates from commercial and sport fisheries (Kohlenstein 1980, Cooper and Polgar 1981). For the Sacramento-San Joaquin Estuary population, major factors limiting production are the initial number of eggs spawned, water temperature, freshwater flow, food supply, predators, competition, cannibalism, diversions, and water quality (Chadwick et al 1977, Turner 1972, Turner and Chadwick 1972, Goyert 1980, Cannon 1981, and DFG 1981).

Number of Eggs Spawned

There is limited evidence from Chesapeake Bay that low numbers of spawners affects yearclass strength. Kohlenstein (1980) points out that the striped bass population in Chesapeake Bay expanded from 1934 to 1970 despite high exploitation of spawners in the commercial and sport fisheries. However, since no strong yearclasses have been produced since 1970, spawning stocks have been severely reduced to the point where the estimated yearclass strength is limited to a small extent (10 to 25 percent of the variability) by spawning stock. Cooper and Polgar (1981), to the contrary, state that yearclass strength does not appear related to number of eggs produced. Kernehan et al (1981) found no positive relationship between the number of eggs spawned and the number of larvae or juveniles produced from 1971 to 1977; their data indicated a negative relationship between the number of eggs and the number of young.

In the Sacramento-San Joaquin Estuary, striped bass have been declining for 40 years, but the decline was not attributed to reduced egg production from limited numbers of spawners (Chadwick 1979). Recently, the California Department of Fish and Game (1981, unpublished report) presented evidence that the adult population has now declined to where it appears that the yearclass strength may be limited by the number of eggs produced. Since the early 1970's, egg production appears to have declined by as much as 90 percent.

Water Temperature

Temperature may be an important factor in the Sacramento-San Joaquin Estuary because temperature is often less than optimal for growth. At marginal temperatures (16 to 20C) young bass grow slowly and thus remain in the higher mortality early life stages for longer periods. At more optional temperatures (22 to 24C) occurring in the Delta and Suisun Bay during the summer of warm years, the growth and survival potential is high if food supply is sufficient. The poor yearclass in 1980 may have resulted from the below-normal temperatures (18 to 20C) during June and July in the western Delta and Suisun Bay (Cannon 1981).

Food Supply

As stated earlier, growth and survival are strongly related to abundance and availability of food supply. The strong yearclasses are probably produced when dense and sustained patches of zooplankton are available to larval striped bass during their first month of life. After this period, juveniles are able to feed on larger more diverse invertebrate forms; juvenile survival is probably related to abundance of these organisms.

The extent and degree of zooplankton patchiness may be an important factor in early larval survival. Owen (1981) has conducted a series of microscale plankton collections off the coast of Southern California and found that localized densities within phytoplankton patches approach prey densities required to sustain larval anchovy growth as determined in laboratory studies. A similar phenomenon may be operating in larval striped bass nursery areas. Little is known about microscale distribution of zooplankton in the Bay/Delta or what factors influence it.

The condition and composition of the zooplankton food supply are also important. Highly productive zooplankton with abundant food and a high reproductive rate would be less vulnerable to overgrazing. The availability of certain sizes or ages of zooplankton may also be important. Only the smallest newly hatched zooplankton are important to first feeding larval striped bass. Larval bass are also highly selective feeders and may only feed on certain species of zooplankton.

The high correlation reported between yearclass strength and Delta Outflow Index in the Sacramento-San Joaquin during the spring and early summer is probably related to the production of food within the system (Turner 1972, Turner and Chadwick 1972, Chadwick et al 1977, and Cannon 1981). At intermediate and high flows, the timing, magnitude, and duration of zooplankton production in the Delta and Suisun Bays with striped larvae is probably good in most years. With high flows, the entrapment zone is located in San Pablo or Suisun Bays where maximum phytoplankton standing crop occurs (Cloern 1979, Ball and Arthur 1979) and highest standing crops of zooplankton develop (Arthur and Ball 1979).

Freshwater Inflow

Freshwater inflow during the spring disperses eggs and larvae from upriver spawning grounds into the bays and Delta. Turner and Chadwick (1972), Chadwick et al (1977), and Stevens (1977) believe inflow is an important factor in subsequent survival of striped bass. High flows may be important to disperse larvae into San Pablo and Suisun Bays, and the entrapment zone where highest densities of zooplankton occur (see Arthur and Ball 1979 and 1980). Low flows (under 5000 cfs) confine the entrapment to Delta channels where food production and space is reduced.

To illustrate this point, data from egg and larvae surveys in different years were compared. A comparison of downstream movement of larvae in 1972 (a dry year with an average May outflow of about 5,500 cfs and June outflow of 3000 cfs) and 1973 (a normal year with an average May outflow of about 12,000 cfs and June outflow of 7000 cfs) indicates very little difference in rate of movement to the western delta (DFG et al 1974, p. 20). However, surveys of eggs and larvae made by CDF&G for the two years indicate that in 1973 about 20-40 percent of the early larvae (3 to 10 mm) eventually reached eastern Suisun Bay as compared to less than 10 percent in 1972 (see Appendix A and Appendix B). This difference may have contributed, in part, to the much larger yearclass (over twice as high) in 1973. A possible complicating factor in 1972 was the Andrus Island break which caused the June low in Delta outflow. From all indications (see Appendix C) the break may have been instrumental in poor survival in 1972.

Further review of the egg and larvae survey data indicates that in the high flow years (1967, 1969, 1971, and 1975) 50 to 80 percent of the larvae reached Suisun Bay. In the drier years (1968, 1970, 1976, and 1977), less than 4 percent of the early larvae reached Suisun Bay. The high flow years all produced fair to good yearclasses as did 1970 and 1973. In 1970 and 1973 flows during May and June were sufficiently high (they averaged 11 to 12 thousand cfs in May and 6 to 7 thousand cfs in June) to maintain at least part of the entrapment zone in Suisun Bay. In the dry years, flows averaged less than 5,000 cfs in June and survival of young was poor.

Predators

Little is known about predation on striped bass young. The only major predators found in abundance in the Delta and Suisun Bay are Sacramento squawfish and yearling and older striped bass. Stevens (1966a) reported significant cannibalism of young bass by older bass. The extent of predation and cannibalism mortality is not known.

Competition

Young bass must compete for habitat and food supply with other young bass and other species of fish and invertebrates. Competition with other bass entails density-dependent mortality where at densities higher than the capacity of the habitat, food supply per individual is limited or the prey are overgrazed resulting in reduced growth rate and higher eventual mortality rate. This mechanism can occur on a large or small scale and may be an important factor in the food supply-growth-survival relationship.

Competition with other organisms (interspecific competition) has the same consequences as competition among organisms of the same species (intraspecific competition). Organisms compete for finite habitat and prey resources. The major competitors of larval striped bass are larvae of other species and invertebrates which feed upon the same prey. Other fish young in the Bay-Delta are the Pacific herring, northern anchovy, threadfin shad, smelt, gobies, sculpins, American shad, and chinook salmon. The smelt, herring, sculpin, and young salmon are prevalent earlier than the striped bass young (PG&E unpublished data). Threadfin shad occur earlier and further upstream in freshwater, although all lifestages of threadfin probably compete with young bass for zooplankton in the north, central, east, and south Delta during the spring. Goby young are present during the spring and summer in low numbers and may compete with young bass. Anchovy larvae are abundant during the summer, but concentrate more seaward in the lower Bays. Some American shad spawn about the same time that striped bass do in the Delta, although most spawn later in tributary streams. Larval American shad feed on zooplankton during the summer and may compete with young bass in the north and east Delta. Few American shad larvae are found in the western Delta or Bays.

Of the invertebrates, Crangon and Palaemon shrimp feed on similar food as the striped bass young, however, these shrimp concentrate more seaward in slightly higher salinity waters during the spring and summer (PG&E unpublished data). Larval forms of Palaemon do move upstream and concentrate in Suisun Bay low salinity waters during the summer and may offer striped bass significant competition for Neomysis, the principal prey of both species. Since Palaemon were only first observed 25 to 30 years ago, they may have only recently become a significant competitor. If they consume a significant proportion of the Neomysis production, they may be taking significant potential production capacity from striped bass.

Diversions

Significant water diversions in the Delta include the state and federal Delta pumping plants, Delta agriculture diversions, the Contra Costa Canal, and two PG&E power plants (see Figure 1 for locations). In addition, the Delta Cross-Channel diverts Sacramento River water into the Central Delta for conveyance to the Delta pumping plants. The proposed Peripheral Canal would divert Sacramento River water from a point about 10 km further upstream at Hood. Flow rates of these diversions are:

CONSUMPTIVE (cfs)

Delta Pumping Plant	3000-6300
Tracy Pumping Plant	3000-4600
Delta agriculture (total)	2000-5000
Contra Costa Canal	200-500

NON-CONSUMPTIVE (cfs)

Delta Cross-Channel	3000-10000
Pittsburg Power Plant	1600
Contra Costa Power Plant	1500

Three potential effects from these diversions are: reduction in the outflow to the bays (consumptive diversions only); increase in Delta channel velocities (pumping plants); and entrainment or entrapment of young bass at their intakes. Reductions in outflows affect the carrying capacity of the estuary by: (1) reducing input of detritus and nutrients that would otherwise be available to the estuary; (2) reducing freshwater flow to the estuary thereby changing the mixing zone hydraulics and shifting the entrapment zone upstream into less productive channels; (3) increasing flows and turbidity in Delta channels thereby reducing phytoplankton and zooplankton production; and (4) altering the natural flow direction from seaward toward the south Delta pumping plants during low flow periods.

The impact of the diversions depends on their magnitude and the amount of total inflow to the estuary. At high flows the percent diverted is lower, shifts in the entrapment zone are minimal, and flow regimes are altered little. During the period 1959 to 1976, high flows occurred only in 1967 and 1969, two extremely wet years with high June through August inflow; less than 20 percent of the Delta inflow was lost to Delta pumping plants in June and July of these two years. In all other years, the percent of Delta

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inflow diverted ranged from 35 to 78 percent, with 60 to 78 percent diverted during dry years and 35 to 48 percent diverted in wetter years (CDF&G 1976).

Both Delta Outflow and percent diverted are highly correlated with yearclass strength of striped bass from 1959 to 1976 (CDF&G 1976 and Chadwick et al 1977). Chadwick et al (1977) concluded that both direct losses and flow changes affect yearclass strength.

Evidence available indicates that the predominant factor on the carrying capacity of the estuary is the flow effect . For example, in 1976 and 1977, the two driest years with very poor yearclasses produced, very low numbers of young bass were observed at the Delta pumping plants. In addition, years such as 1974 with moderate flows and relatively large yearclasses had high or highest losses at the Delta pumping plants. Furthermore, yearclass strength appears to be set before July-August peak of losses at Delta pumping plants. These conclusions are based on salvage data available at the pumping plants which only include juvenile bass. The extent of losses of eggs and larvae at the pumping plants are not known.

Direct losses at the diversions may play an important part in the subsequent size of the yearclass and the fishable stock. If there is no density-dependent adjustment in mortality (that is no higher survival of remaining young because more food and space are available), then yearclasses will be reduced by losses of young. Subsequent stocks of fishable adults would also be reduced. The reductions will be proportional to the percentage of young lost to diversions, which are higher in drier years. If yearclass strength is set during the larval stage as discussed earlier, then diversion loss of larvae are likely to have less effect because of density-dependent and density-independent factors controlling the survival of larvae. Losses of juveniles after yearclass is set would have the proportional direct affect discussed above.

If stock levels are dangerously low and the number of eggs spawned affects subsequent yearclass strength, then losses at diversions would affect future egg production as well. Under these circumstances, the reductions in the stock will be greater than the percentage of young lost to diversions. The effect would be similar to compounding interest. For example, a 5 percent loss per year would cause a 40 percent reduction in the population after 10 years, where if eggs were not limiting the population would have been only reduced by 5 percent after 10 years.

The absolute effect of diversions is difficult to determine because the high variability in yearclass strength from year to year, due to changing environmental conditions, masks the lesser but possibly important effects of diversion losses.

Water Quality

Recent evidence presented by Dr. Jeanette Whipple of Tiburon Laboratory of the National Marine Fisheries Service suggests that toxic substances may be reducing health and survival of adult striped bass. Such effects would be important to the viability of the stock if the production of eggs were limited and related to subsequent production of young. If egg production is not limiting, then the principal effect would be limited to an adult population of poor health and reduced numbers. The consequences in either case are serious if the extent of these maladies is sufficiently high. The extent of this problem will not be known until Dr. Whipple and the State Water Resources Control board complete their studies.

Factors Related to Decline of Striped Bass In the Sacramento-San Joaquin Estuary

1940 to 1976

Party boat catch data collected since 1940 (Stevens 1977) indicate a gradual long-term declining trend from 1940 to 1976. Stevens (1977) related the decline to reductions in June-July outflow. Cannon (1981) using the same information related the decline to reductions in May and June outflow. Recently, the adequacy of the party boat catch data to represent long term patterns in adult abundance has been questioned (D. Steven, Fish and Game, personal communication).

1959 to 1978

CDF&G summer tow-net survey data collected from 1959 to 1978 (excluding 1966), indicate a positive correlation between young abundance and Delta outflow and negative correlation with diversion rate. Chadwick et al (1977) related young abundance in Suisun Bay over the period to June-July outflow and diversions and abundance in the Delta to May-June outflow and diversions. Chadwick (1979) after adding 1977 and 1978 data found Neomysis abundance associated directly with young bass, as well as outflow and diversions. Goyert (1980) developed an index from the same summer townet survey data for 1961 to 1977 and found young abundance correlated highly with May outflow. June outflow was only slightly less correlated. A common conclusion of these studies is the strong correlation between striped bass young production estimates and spring (April through June) freshwater flow.

? May-July.

1977-1981

From 1977 to 1981 the index of young summer abundance was much lower than expected based on relationships developed between the index and outflow and diversions from 1959 to 1976. CDF&G (1981) believes the decline is due to low numbers of spawners and a decline in food abundance. Cannon (1981) suggests the poor production in 1978 and 1979 may be due to unusual outflow patterns in 1978 and 1979. The 1978 outflow declined from an average of 40,000 cfs in May to 9000 cfs in June, by far the largest fractional reduction in May-June flow from 1959 to 1980. In addition, flows during June 1978, declined from 15 to 20 thousand cfs during the first week of the month, to less than 5 thousand cfs during the last two weeks of the month, thus causing the entrapment zone to move rapidly into the Delta channels resulting in poor food production. In 1979, flows in late April and early May declined sharply to levels below 5000 cfs which resulted in the entrapment moving into the Delta channels, an event which previously had only occurred in drought years. For 1980 and 1981, preliminary indications are that phytoplankton production was unusually low in the Delta and possibly Suisun Bay (J. Arthur, U.S. Bureau of Reclamation). Either poor egg production or poor food supply or both could have caused the low young abundance from 1977 to 1981.

A further theory, perhaps related to that of Cannon's (1981), is that the food supply of young striped bass was poor at least from 1977 to 1979. This theory is supported by phytoplankton survey data collected since 1969 (Cloern 1979, Ball and Arthur 1979, and Arthur and Ball 1980). Phytoplankton blooms, as summarized in Table 1, were poor in 1977, 1978, and 1979. Years 1977 and 1979 were dry years with the entrapment zone located in the Delta during portions of late spring and early summer. Since phytoplankton are known to be an important food of Eurytemora, Daphnia, and Neomysis in the Bay-Delta, the abundance of these key prey of young bass was probably poor as well.

TABLE 1 - Characterization of Phytoplankton Blooms in Late Spring and Summer of 1969 to 1979 in Sacramento-San Joaquin Estuary

	Late Spring			Early Summer			Striped Bass Index
	San Pablo	Suisun	Delta	San Pablo	Suisun	Delta	
1969	Poor*	Poor	Poor	Good	Good	Fair-Good	Good
1970	Fair	Good	Fair	Fair	Good	Fair	Good
1971	Poor	Good	Poor-Good	Poor	Good	Poor-Fair	Good
1972	Poor	Fair	Fair	Poor	Good	Poor-Fair	Poor
1973	Fair	Good+	Good+	Poor	Good	Poor	Good
1974	Fair	Good	Poor-Fair	Poor	Fair	Poor-Fair	Good
1975	Fair	Fair	Poor-Fair	Poor	Good	Poor	Good
1976	Poor	Good	Good	Poor	Fair	Poor	Poor
1977	Poor	Poor	Poor	Poor	Poor	Poor	Poor
1978	Poor	Poor	Poor	Poor	Poor	Poor	Poor
1979	Poor	Poor	Poor	Poor	Fair	Poor	Poor

* Poor $<$ 10 mg/l chlorophyll
Fair $\approx$ 10-20 mg/l chlorophyll
Good $>$ 20 mg/l chlorophyll

Data Source: Cloern 1979, Ball and Arthur 1979, Arthur and Ball 1980.

SUMMARY AND CONCLUSIONS

Factors Controlling Production of Young Striped Bass

The principle factors controlling the production of young striped bass in the estuary are probably temperature and food supply. Temperature provides the potential for growth and production of food supply. The food supply fills the potential for growth. Growth rate is closely related to mortality rate since larger young can feed on larger more diverse prey and avoid predators.

Temperature and food supply are controlled by freshwater inflow and solar radiation. Freshwater inflow sufficient to maintain the entrapment zone in the shallow bays of the estuary produces the greatest blooms of phytoplankton and the zooplankton food supply of striped bass. Freshwater inflow is necessary to maintain the position of the entrapment zone as well as to bring the essential nutrients for phytoplankton and detritivor invertebrates. Freshwater inflow patterns sufficient to maintain the entrapment zone in Suisun Bay during the important spring striped bass rearing peiod have not occurred since 1975 with the exception of 1980.

Habitat is also important. The shallow low velocity and high turbidity habitat of the Bays is optimal for feeding and rearing of young bass. High freshwater flow provides more of this habitat to young bass by dispersing them into and maintaining them in the shallow bays of the estuary where food is greatest.

Adult spawners and egg production may be limiting at low adult abundance. However, carrying capacity is probably far more limiting. The number of recruits may be significantly reduced at low levels of spawners, but large yearclasses can probably still be produced with the right environmental conditions even when spawner abundance is low. Such conditions have not occurred since 1975.

Losses of young bass at diversions and power plants are potentially important at low adult stock levels. Losses may reduce poor yearclasses significantly since poor yearclasses are usually associated with low outflow when diversions have their greatest impact. At lower stock levels, the added losses at diversions may accelerate the decline in the population.

Water quality problems may be causing increased mortality of adult fish, thus allowing fewer to spawn. Toxins may also be reducing the survival of eggs spawned by hindering embryo development. Both mechanisms could reduce the recruitment potential per spawning adult.

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IV. OTHER FISHES

IV. OTHER FISHES

Other important fishes that are dependent at least in part on the estuary are the Pacific herring, American shad, northern anchovy, white sturgeon, threadfin shad, several species of smelt, rockfish, starry flounder, and English sole. Most of these species use the estuary's freshwater, mixing, or marine zones for spawning and/or rearing of young. The sturgeon, threadfin shad, and smelt are probably dependent on environmental conditions in the estuary in much the same way as the salmon, striped bass, and American shad. The other fish are marine forms that use the lower estuary (San Francisco and San Pablo Bays) as nursery areas.

The most important factors in the survival of young of the marine species are probably upwelling and freshwater inflow. Both supply necessary nutrients and food to the Bays and control the physical and chemical characteristics of the estuary. High flows in winter and early spring in association with increasing temperature and upwellings cause the plankton blooms in the Bays. High flows also bring the organic detritus which helps feed the complex zoobenthic food chain. Changes in the magnitude or timing of these production cycles may also affect fish populations. More information is needed on these production cycles, the dependence of the biological community on them, and the potential effects of man's activities on the system.

PACIFIC HERRING

Pacific herring depend upon the lower estuary for spawning and early rearing. The adults move into the Bay from the ocean in late fall and winter to spawn (Ganssle 1966). Most spawning takes place near Tiburon and Sausalito from late December to March. In studies in Alaska, Carlson (1980) found Pacific herring moved into shallows to spawn when water temperatures increased and high turbidity and plankton blooms appeared. This suggests that Pacific herring may require high flows and turbidities during the winter and associated plankton blooms as cues for spawning. The high turbidity would provide protection from predators.

Newly-hatched larvae are abundant in the Bays in February and March (Ganssle 1966). Juveniles are abundant from April through June (Ganssle 1966, Messersmith 1966). Young herring apparently migrate to coastal waters by summer possibly due to increased water temperature in the estuary.

Yearclass strength of Pacific herring is dependent on survival during the initial inshore rearing period of the young after spawning (Carlson 1980, Hourston 1958). Survival is most likely tied to production of zooplankton in the Bays during the winter when larvae are prevalent and spring when juveniles are abundant. Since the principal food of the larvae and juveniles is calanoid copepods (Simenstad et al 1979, Hart 1973), survival and yearclass strength are probably related to the production of Acartia clausi, the most abundant marine copepod in the lower estuary. Acartia in turn are dependent on phytoplankton blooms which are dependent on nutrients from upwellings and freshwater inflow.

AMERICAN SHAD

American shad is a member of the herring family that was first introduced to the Sacramento-San Joaquin system from releases of Hudson River, New York shad from 1871 to 1881. The largest run of adult American shad is in the Sacramento River and its tributaries including the Feather, Yuba, and American Rivers. Shad support an important sport fishery in the Sacramento River and its tributaries. The American shad is an anadromous fish which spends several years in the ocean before migrating through the estuary to the freshwater rivers in the spring of the year to spawn. Eggs are spawned in freshwater. Young spend most of their first year in rivers before migrating to the ocean in the fall. Estuaries provide migratory, spawning, and nursery habitat for American shad. Environmental conditions within the estuary affect the survival and growth of young and the eventual recruitment to the adult population.

The Delta portion of the estuary (especially the lower Sacramento River) is an important nursery area for young American shad in the summer and the fall

(Ganssle 1966, Stevens 1966b, and California Department of Fish and Game et al 1974). Environmental conditions during this nursery period are probably a major factor in the population dynamics of the Sacramento population. Temperature and food supply are the major factors which control survival and yearclass strength. Temperatures below 20C may limit growth and survival (Marcy 1976). Copepods and cladocerans are the primary food of young shad (Stevens 1966b). Freshwater inflow to the Delta is the important factor in temperature and food supply. The period of greatest importance is late spring and early summer when newly hatched young are present in the system.

V. IMPORTANT INVERTEBRATES

V. IMPORTANT INVERTEBRATES

The invertebrates identified as being most important as food of young fish in the estuary are the zooplankton and epibenthic crustaceans. The principle zooplankton are the calanoid copepods and the cladocerans. The major epibenthic crustaceans are amphipods, mysids, and decapod shrimp and crabs. The zooplankton are important in the diet of many fishes with planktonic or nektonic young including striped bass, chinook salmon, American shad, Pacific herring, and northern anchovy. The epibenthic crustaceans are important food to sturgeon, striped bass, and chinook salmon.

The life histories of these important invertebrates are complex as are their environmental requirements. They are generally dependent on the estuary for food and habitat. Copepods, cladocerans, and mysids are primarily herbivors and depend on phytoplankton blooms to sustain growth, survival, and reproduction. Amphipods are detritivors and feed on organic debris and associated microorganisms. The decapod shrimp and crabs are carnivors which feed on the herbivors and detritivors.

Other invertebrates that play important roles in the estuarine food web include harpacticoid and cyclopoid copepods, polychaetes, rotifers, annelids, clams and mussels, and a diverse fauna of other crustaceans. These are not discussed here because they are not principal prey of the fish species previously discussed, although they are probably important in the organic carbon cycle or as food to other fishes and invertebrates.

CALANOID COPEPODS

The calanoid copepods, *Acartia clausi* and *Eurytemora hirundoides*, are the dominant calanoid copepods in the estuary and are an important prey to carnivorous invertebrates and fish. Both species feed principally on phytoplankton. *Acartia* concentrate in the marine portion of the estuary at

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salinities greater than 10 ppt (Painter 1966, Arthur and Ball 1979). In wet years they are confined to San Francisco Bay and San Pablo Bay. In dry years they may move into Suisun Bay and the western Delta. Eurytemora concentrate in the entrapment zone of the estuary at salinities less than 10 ppt (Painter 1966, Arthur and Ball 1979).

The greatest production of Acartia and Eurytemora occurs in the spring as phytoplankton bloom and temperature increases. Painter (1966) found highest concentrations in the shallows of San Pablo Bay from March through June of 1963. They were somewhat less abundant in the channels and Suisun Bay from May through July. Concentrations of Acartia of 100,000 per cubic meter in San Pablo Bay such as occurred in the spring of 1963 probably contribute significantly to growth and survival of young Pacific herring and other fishes. Similar concentrations of Eurytemora also occurred in the entrapment zone in the spring of 1963 and may have been a significant factor in the strong yearclass of striped bass produced that year.

The timing of the blooms of Acartia and Eurytemora depends on phytoplankton blooms and water temperature. In Narragansett Bay, Rhode Island, Durbin and Durbin (1981) found Acartia to have a high productive capacity capable of increasing growth, survival, and reproduction rapidly when phytoplankton bloom and water temperature reach 15 to 20C. They also found Acartia grazing to effectively reduce the spring bloom of phytoplankton such that Acartia subsequently declined. CDF&G (1974, 1978, and 1980) observed Acartia and Eurytemora abundance in the Sacramento-San Joaquin Estuary to be closely related to chlorophyll and phytoplankton concentration. Estuary temperatures typically warm to 15C in March or April (Conomos 1979, PG&E unpublished data). Earliest phytoplankton blooms occur in the shallows of San Pablo Bay (Ball and Arthur 1979), corresponding to the high early spring blooms of Acartia found by Painter (1966).

The distribution in time and space of these copepod blooms with that of newly hatched larval Pacific herring and striped bass is probably a key factor in the survival and yearclass strength of these fishes. Pacific herring larvae are prevalent in the lower bays from February through April. Early blooms in San Pablo Bay may be an important factor in their survival. Striped bass early larvae which reach San Pablo Bay, Suisun Bay, and the western Delta during May and June feed on Eurytemora. Sustained high concentrations of Eurytemora may be an important factor in the survival of the young bass.

CLADOCERANS

The cladocerans of the genus Bosmina and Daphnia are important prey of young American shad, striped bass, and chinook salmon young. Young fish generally prefer the larger Daphnia (Craddock et al 1976, Beaven and Mihursky 1979).

Cladocerans concentrate in the freshwater portion of the estuary during the warmer period of the year. Studies in the Sacramento-San Joaquin Estuary in the early 1960's by Painter (1966) and Turner (1966) indicate that cladocerans were most abundant during the summer in the Delta as temperature increased and flows in channels declined. Turner observed greatest concentrations in the higher nutrient waters of the San Joaquin River with net velocities from 0-0.1 ft/sec. In the Columbia River, Craddock et al (1976) noted blooms occur as flows declined and temperatures reached 20C in early summer. Blooms of cladocerans occur in the Potomac Estuary in May and June as temperatures warm and flows decline (Setzler-Hamilton et al 1981). Late spring blooms may occur in the Delta during warm years. In 1978, Daphnia blooms developed by early May in the Sacramento ship channel, Cache Slough and Sacramento and San Joaquin River channels (PG&E unpublished data).

The timing and extent of the cladoceran bloom in the freshwater portion of the estuary may be an important factor in the survival and yearclass strength of young striped bass. Setzler-Hamilton et al (1981) suggest this as a possible mechanism in determining striped bass yearclass strength in the Potomac Estuary. Since newly hatched striped bass larvae generally reach the Delta in May from the Sacramento River, warmer temperatures (20C or higher) during this period would result in greater growth potential and higher food supply, and thus greater survival.

MYSIDS

Mysids are small shrimp-like crustaceans. The major species in the estuary is Neomysis mercedis which is an important prey of striped bass, chinook salmon, sturgeon, and other fishes, and carnivorous invertebrates.

Neomysis feeds on phytoplankton, detritus, and zooplankton (Orsi and Knutson 1979, Kost and Knight 1975). Phytoplankton is probably the major food in the Sacramento-San Joaquin Estuary (Orsi and Knutson 1979). In the Columbia River Estuary, small crustaceans are more important in the Neomysis diet (Houghton et al 1981) probably because phytoplankton concentrations are lower in the Columbia River Estuary than in the Sacramento-San Joaquin Estuary.

Neomysis are most abundant in the entrapment zone of the estuary. Heubach (1969) and Orsi and Knutson (1979) found Neomysis most abundant from freshwater to low salinity. Siegried et al (1978) found Neomysis most abundant from 2 to 10 millimhos per cm conductivity. Reproduction centers at the freshwater end of the entrapment zone. High channel flows above 0.4 fps (0.12 mps) appear to limit their upstream penetration (Orsi and Knutson 1979).

Abundance of Neomysis is controlled by food supply, temperature, and predators. The population expands rapidly in the spring as temperature increases and phytoplankton bloom (Siegfried et al 1979). Spring-summer abundance is related to phytoplankton abundance and Delta outflow (Orsi and Knutson 1979). High summer temperatues above 22C cause stress and mortality to Neomysis (Sitts 1978, Heubach 1969). High temperatures and high predation rates by fish and carnivorous invertebrates along with reduction in phytoplankton blooms and reproductive rates may cause a summer decline in the spring production of Neomysis. Movement of the entrapment zone into Delta channels at low summer flows results in a population decline (Siegfried et al 1979). With the entrapment zone in Delta channels, phytoplankton concentrations decline (Arthur and Ball 1979). Also at lower flows, water temperature usually increases and input of nutrients and detritus declines.

The timing and magnitude of the spring-summer production of Neomysis may be an important factor in the survival of young striped bass. After the early larval period when young bass feed on copepods and cladocerans, small Neomysis become their principal prey. Having an abundant supply of young Neomysis available during the late larval and early juvenile period provides for high growth and thus high survival. A decline in Neomysis during the summer may contribute to lower growth rate and poorer survival of young striped bass.

The occurrence of an early spring bloom of Neomysis in San Pablo and Suisun Bays may improve growth and survival of young chinook salmon which would be present after high winter and early spring flows.

A good production of Neomysis in the spring and subsequent high survival of the brood under optimal temperature and phytoplankton concentration also provides for high second generation production in late summer and early fall which may be important in sustaining juvenile striped bass through the late summer, fall, and winter.

AMPHIPODS

Amphipods most commonly preyed upon by fish and most abundant in the estuary are two species of Corophium, Corophium stimpsoni and Corophium spincorne. Both species are considered zoobenthos (Hazel and Kelley 1966) because they dwell on and feed in bottom sediments. They are principally detritivors.

Corophium are most abundant in freshwater or low salinity low velocity areas of the estuary which includes the Suisun Bay and the Delta. Hazel and Kelley (1966) found them most abundant in areas of the Delta where current velocities ranged from 0.05 to 0.20 fps with a peak at 0.10 fps. C. spincorne were most abundant in shallow water in peat or cobble substrate. C. stimpsoni were most abundant in deeper channels with sandy bottoms. Siegfried et al (1978) noted that Corophium produce two generations per year, one in spring-summer and one later in summer-fall. The spring reproduction begins in March probably as temperatures begin to warm in the Delta.

Corophium are an important food source of young chinook salmon and striped bass which are abundant in the Delta during the spring. The spring production or bloom of Corophium probably is limited by temperature, detritus food supply, and habitat. At high freshwater inflows and rising temperatures, food supply and growth and production rates are probably optimal. The major limiting factor may be low velocity freshwater habitat. High flows in Delta channels due to Delta pumping plants probably limits habitat and production of Corophium as does upstream incursion of salt water into Suisun Bay and the Delta.

DECAPOD SHRIMP

There are two species of decapod shrimp that are important food of fishes in the estuary, Crangon franciscorum and Palaemon macrodactylus. Both are important prey of striped bass and sturgeon.

Adults of Crangon and Palaemon reside in the cooler, more marine waters of the bays while larvae and juveniles move upstream with high salinity bottom currents into the mixing zone of the estuary in the summer. Khorram and Knight (1977) noted adult Crangon concentrate in waters of 18 to 20 ppt salinity at 15 to 17C and young distributed upstream to about 1 ppt at the upstream end of the entrapment zone. Siegfried et al (1978) noted larval Crangon were abundant in bay waters of 10 to 20 ppt salinity from January to June; older young moved into the Delta in the summer as higher salinity water moved upstream and young moved upstream in bottom waters. Young Crangon reached concentrations as high as 6 per cubic meter in the entrapment zone in 1976.

Palaemon larvae apparently concentrate near bottom or are spawned further upstream because they are found further upstream than Crangon larvae. Siegfried et al (1978) indicate that Palaemon breeds from April to October in more marine portions of the estuary and larvae reach the mixing zone in numbers as high as 60 per cubic meter in the summer. Plankton surveys in 1978 (PG&E unpublished data) indicate larval Palaemon to be most abundant (up to 40 per cubic meter) in intermediate salinity waters downstream of the entrapment zone during July. Surveys by Siegfried et al (1978) in 1976 indicate a similar distribution as larval abundance declined sharply upstream of the lower end of the entrapment zone (6 to 10 millimhos per cm) in July; older larvae were more concentrated (up to 5 per cubic meter) in the entrapment zone during August survey. Their distribution appears to be limited by high summer water temperatures (Siegfried et al 1978).

Both Palaemon and Crangon young are carnivorous. Sitts (1978) observed that both species feed predominantly on Neomysis. Other prey include crab larvae (Rhithropanopeus harrisii) and Corophium (Siegfried et al 1978).

In addition to their importance as prey of fish, these shrimp are also competitors with each other and young striped bass. Sitts (1978) and Carlton (1979) suggest possible competition between Palaemon and Crangon because of the overlap of their food habits and distribution. The introduction of Palaemon from the Orient in the 1950's (Carlton 1979) and subsequent establishment may be causing competition with striped bass as well as Crangon. Energy for growth of striped bass and Crangon diverted to Palaemon may be contributing to a decline in the carrying capacity of the estuary to produce both striped bass and Crangon.

The production of Crangon and Palaemon probably depends on conditions affecting larval and young survival. Factors which limit production of crustacean prey especially Neomysis probably limit Crangon and Palaemon. Water temperatues in excess of 18C and salinity distribution may also be important factors.

DECAPOD CRABS

Dungeness crab (Cancer magister) is a valuable commercially harvested crab in central and northern California. Juvenile Dungeness crabs migrate into the bays of the estuary from the ocean to rear. Residence of young crab in the estuary may be important in their overall survival and production (Tasto 1979).

Tasto (1979) found larvae of San Francisco Bay area Dungeness in the Gulf of Farallones while most juvenile occupied the San Francisco Bay complex. To determine the importance of each of these life history stages, he correlated environmental parameters of the ocean and the estuary to adult population size. He found a relationship between oceanic conditions, late larval survival, and yearclass strength in central California coast stocks. Late larval survival probably depends on plankton blooms resulting from later winter and spring upwellings. Analysis did not indicate that conditions in the bays, which may limit juvenile crab survival, limited yearclass strength and subsequent adult population size.

Although upwellings are probably the principal source of nutrients for the plankton community including larval Dungeness in the Gulf of Farallones, outflow of nutrients and detritus during high flow periods may be important during the late winter period of larval Dungeness occurrence. Upwellings generally do not begin in this area of the coast before early spring (Bakun 1975). The major decline in Dungeness landings in central California occurred in the early 1960's (Tasto 1979) and is coincident with five years of subnormal outflow from the estuary from winter 58-59 to 61-62. Poor winter outflow in conjunction with poor upwellings, and the commercial fishery may have contributed to the decline in the stock. Poor spring flows during the same period which may have resulted in poor juvenile survival in the bays may have also contributed to the decline of the Dungeness crab.

Another crab that is possibly important in the estuary is the mud crab, Rhithropanopeus harrisii. This crab was introduced from east coast estuaries in the 1930's (Carlton 1979). Larvae of this crab are planktonic carnivors and are very abundant in the estuary during the spring and summer. They feed on Acartia and Eurytemora copepods and thus complete with other invertebrate planktivors and fish.

VI. ENERGY SOURCES FOR ESTUARY

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Background on the energy sources for biological productivity of the estuary is presented here to provide further insight into factors affecting productivity in the estuary.

ORGANIC CARBON

Organic Carbon is the primary energy source of the estuarine food chain. Sources include organic detritus (debris of dead plants and animals from both terrestrial and aquatic systems) and live plant material (macrophytes, benthic algae, and phytoplankton). Both sources vary in importance with location and time of year in the estuary. Odum et al (1973) states that the primary energy source of estuarine ecosystems is detrital carbon produced within the system (dead macrophytes and algae) and imported by freshwater runoff from the watershed. In describing the organic carbon regime of the Sacramento-San Joaquin Estuary, Spiker and Schemel (1979) identified phytoplankton production as an important source of organic carbon in the low salinity and higher salinity portions of the estuary. Less than one-third of the organic carbon from the lower estuary comes from river-borne sources. In freshwater zones (which varies greatly with freshwater flow) riverine carbon predominates.

The input, storage and release of organic carbon, is a major feature of river-estuary systems that is tied to the systems flow regime and physical-chemical characteristics (Nichols 1979, Cummins 1979). High inflow to the estuary distributes detritus into the bays. At high flow the mixing zone is moved seaward; associated two-layered flow and reduced mixing disperses highly turbid freshwater over the surface of lower estuary waters (D'Anglejan 1981). The location of the freshwater plume in the estuary is influenced by freshwater flow, channel geometry, tidal phase differences, and tidal fluctuations (D'Anglejan 1981).

Estuaries act to trap, store and synthesize organic detritus (Congleton 1976 and Naiman and Sibert 1979). As fresh water reaches the Delta and bays velocity decreases and detritus settles to the bottom, settling is also aided by flocculation (Arthur and Ball 1979). Algae production is high in the bays (due to the shallow low velocity water) contributing significantly to the supply of particulate organic carbon. Invertebrate detritivors increase the supply of available particulate organic carbon by resuspending settled solids and upgrading the assimilative quality of the detritus (Merritt and Wallace 1980). Diatom blooms in adjacent marine waters that develop after upwellings are an important source of organic carbon for estuaries (Malone 1979, Cloern 1979). Pulses of high freshwater flows into the estuary draw high salinity marine waters (and associated diatoms) into the estuary (Malone 1979). The marine diatom blooms correspond to upwellings that occur from late winter to early fall in the San Francisco area of the Pacific Coast (Bakun 1975). While oceanic diatoms may only comprise a small percentage of the organic carbon in bays, they do provide the seed population for blooms that develop within bays (Cloern 1979). Organic detritus, diatoms and other phytoplankton also accumulate in the entrapment zone of the estuary. Arthur and Ball (1980) describe the entrapment zone as the area where upstream moving marine water meets downstream moving freshwater and suspended particles accumulate. Location of the entrapment zone in the shallow bays of the estuary results in increased production of algae and thus additional particulate organic carbon. Adjacent marshes also contribute detrital carbon from the breakdown of marsh plants and from storage riverborn organic detritus (Parker 1975).

Detrital carbon and nutrient input to marine waters from adjacent river and estuarine sources may be important during high winter and spring flow periods. Anderson (1964) and Hobson (1966) found freshwater plumes to influence nutrients and plankton production offshore of the mouth of the Columbia River. Organic carbon from the Sacramento-San Joaquin Estuary may provide a significant source of nutrients to adjacent marine waters such as the Gulf of Farallones especially during high flow periods. Hobson (1980) noted that traditional spring blooms depleted nutrients in coastal marine waters and the only production occurred from upwellings or inputs of nutrients from inshore waters.

The complex nature and importance of detritus in estuarine food webs make analyses of food pathways difficult (Haines and Montague 1979). Where some animals feed directly on detritus, others feed on the microorganisms growing and feeding on the detritus.

The form of the detrital food source varies greatly. Merritt and Wallace (1980) describe major types of organic particles including animal feces, plant debris, and aggregations of suspended solids that have come out of solution. They also describe the important microflora "frosting" on the detritus made up of bacteria, fungi, and other microorganisms. The assimilative-efficiency for detritus in their study ranged between 2 and 20 percent, compared with 30 percent for algae and more than 70 percent for animal issue.

NUTRIENTS

Basic organic and inorganic nutrients are required by primary producers (plants) for photosynthesis especially nitrogen, phosphorus, and silicon. Nutrients are supplied from upstream sources, offshore upwellings, sewage outfalls, and from biological and physical-chemical processes within the system. In the Sacramento-San Joaquin Estuary, most nutrients are supplied by sewage effluents and river inflow (Conomos et al 1979, Peterson 1979). Although the basic nutrients are generally not limiting within the Sacramento-San Joaquin Estuary (Cloern 1979, Peterson 1979, and Silva 1979), inorganic nitrogen and silicon deficiencies may limit phytoplankton production during peak summer production when freshwater inflow is low (Arthur and Ball 1980, Siegfried et al 1979).

VII. IMPLICATIONS AND RESEARCH NEEDS

VII. IMPLICATIONS AND RESEARCH NEEDS

The estuary has an important role as a nursery area of chinook salmon, striped bass, and other fishes. Freshwater inflow to the estuary, which controls the distribution, growth, survival, and production of young fish and their invertebrate food supply is the most important factor controlling the capacity of the estuary to produce young fish. Declines in the populations of salmon and striped bass over the past 40 years are related, in part, to changes that have occurred in the estuary. Reductions in freshwater flow from upstream and within estuary water developments have probably played a key role in the declines. Present winter and spring flows are reduced 30 to 70% from historical levels (see Kelley and Tippets 1977).

Planned future water development will further reduce winter and spring flows by 10 to 50% (see Kelley and Tippets 1977). The potential impacts of further development could be minimized by improved water management to optimize production of fishes and their food supplies given available water. A prerequisite of such a management strategy is a clear understanding of the function of the estuarine ecosystem, the environmental requirements of important species and the role of freshwater inflow. Such understanding is presently incomplete. Until it is, management strategies must be based on the existing information and ecological theory. If carefully managed, the fisheries populations resources of the Sacramento-San Joaquin Estuary could be maintained and possibly increased above present levels. Understanding the environmental requirements of key predator and prey organisms and the production cycle in the estuary should lead to detailed specifications which better control estuary productivity and young fish production.

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APPENDICES

APPENDICES

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APPENDICES, TABLE OF CONTENTS (Continued)

CODES FOR FIGURES

A. APPENDIX A

Region (See Figure 1 for location)

W SUISUN	=	West Suisun Bay
E SUISUN	=	East Suisun Bay
LOWER SAC	=	Lower Sacramento River
LOWER SJ	=	Lower San Joaquin River
UPPER SJ	=	Upper San Joaquin River
UPPER SAC	=	Upper Sacramento River

B. APPENDIX B

GRP 5	=	4-6 mm
GRP 8	=	7-9 mm
GRP 11	=	10-12 mm
GRP 14	=	13-15 mm
GRP 17	=	16-18 mm
GRP 20	=	19-21 mm

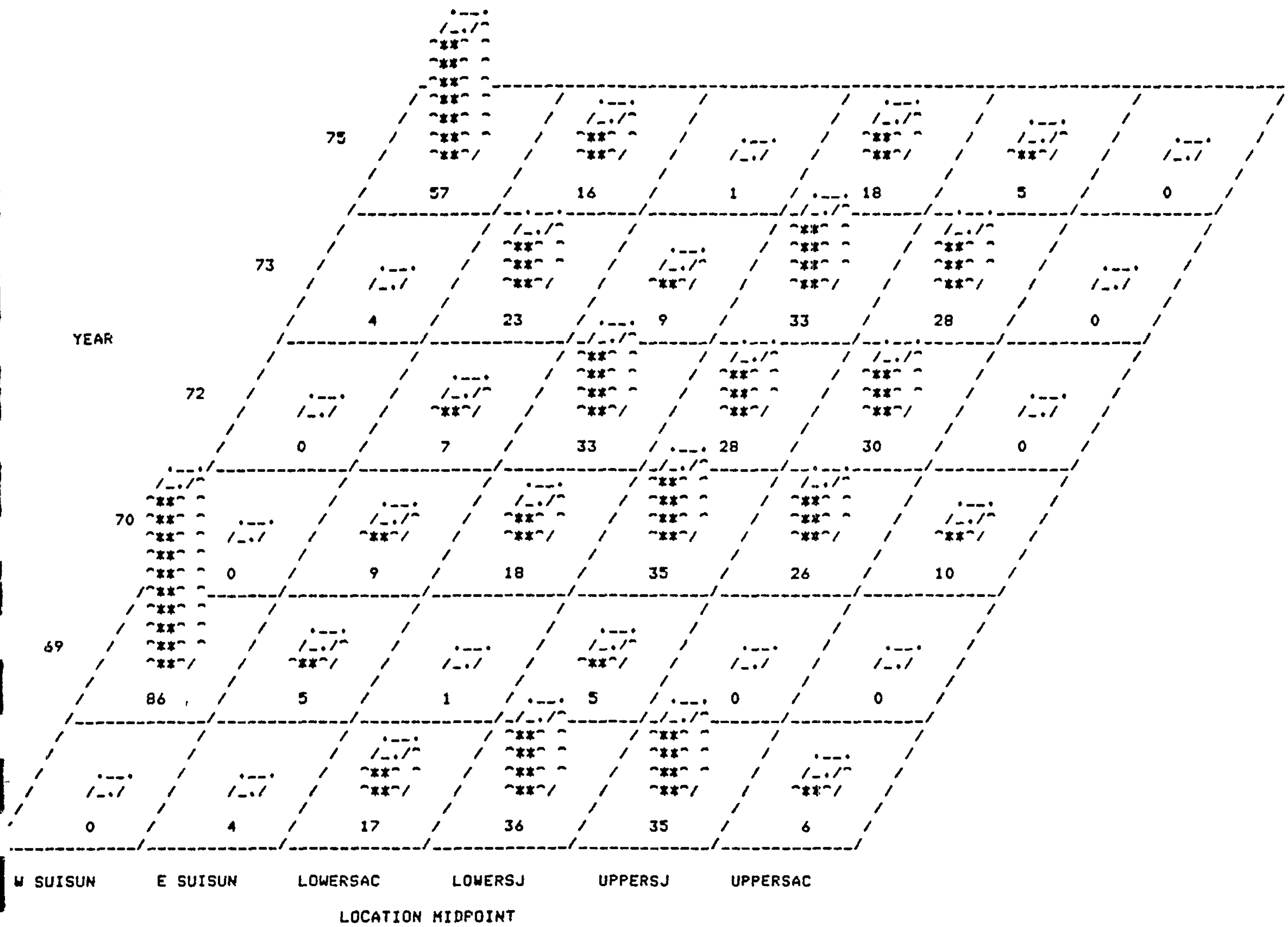
C. APPENDIX C

Size Midpoint

22	=	Midpoint of length interval 20-24 mm
27	=	25-29 mm
32	=	30-34 mm
37	=	35-39 mm
42	=	40-44 mm
47	=	45-49 mm

THE PERCENTAGE COMPOSITION DISTRIBUTION OF STRIPED BASS 7-10 MM
IN THE SACRAMENTO SAN JOAQUIN ESTUARY FOR THE MONTH OF MAY

BLOCK CHART OF SIZE7_10

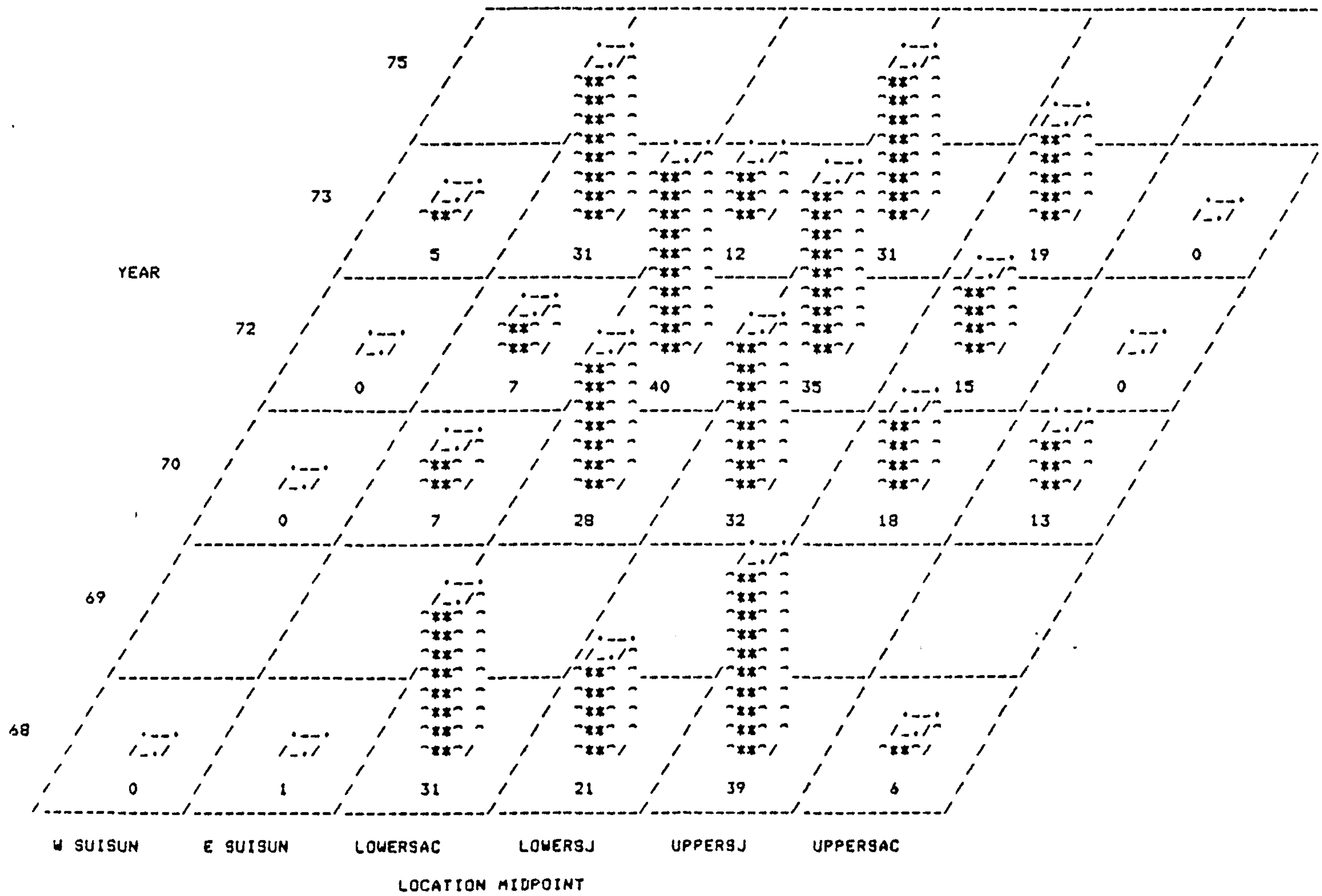


D-019813

D-019813

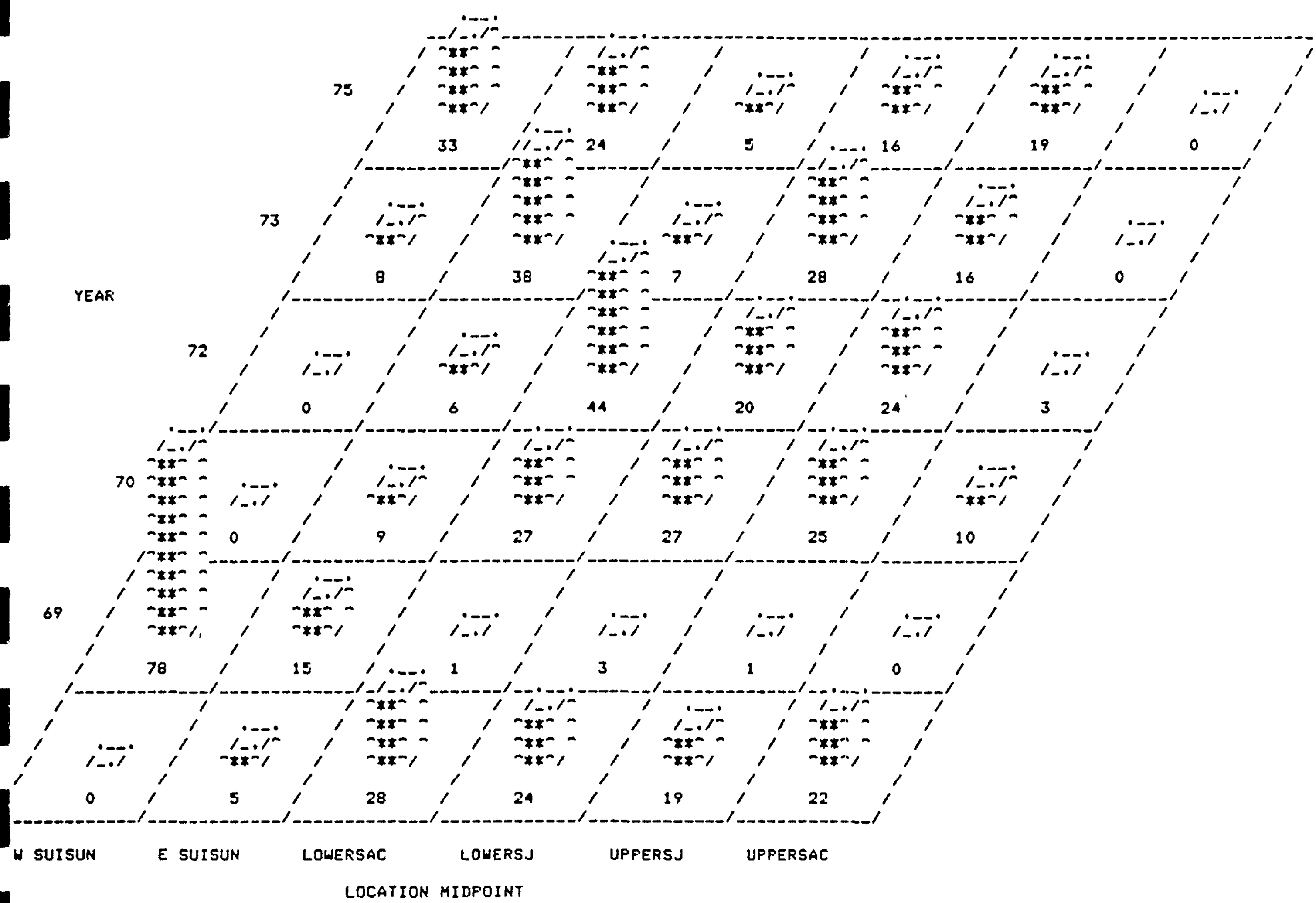
THE PERCENTAGE COMPOSITION DISTRIBUTION OF STRIPED BASS 11-14 MM
IN THE SACRAMENTO SAN JOAQUIN ESTUARY FOR THE MONTH OF MAY

BLOCK CHART OF SIZE1114



THE PERCENTAGE COMPOSITION DISTRIBUTION OF STRIPED BASS 7-10 MM
IN THE SACRAMENTO SAN JOAQUIN ESTUARY FOR THE MONTH OF JUNE

BLOCK CHART OF SIZE7_10



D-019815

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IN THE SACRAMENTO SAN JOAQUIN ESTUARY FOR THE MONTH OF JUNE

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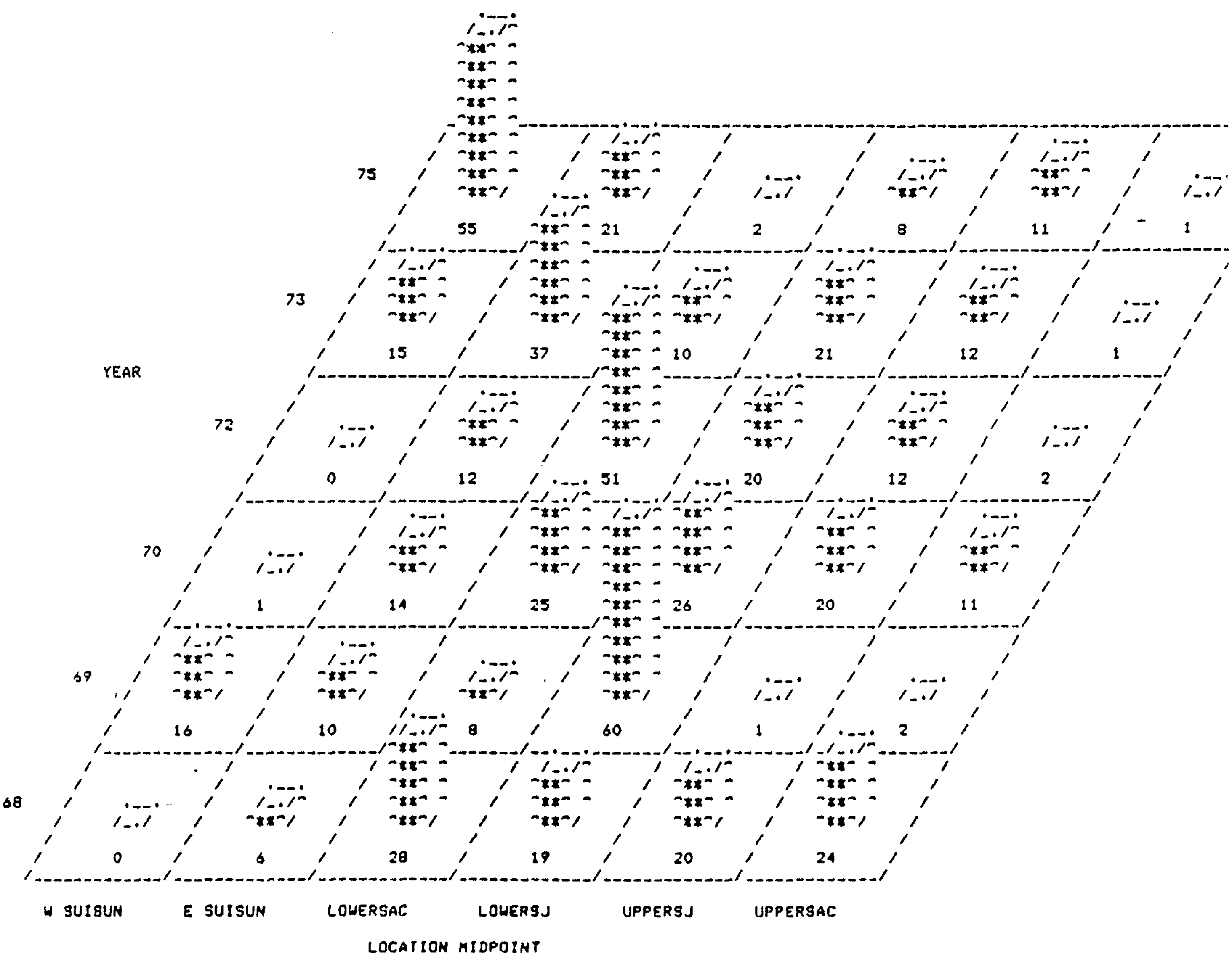
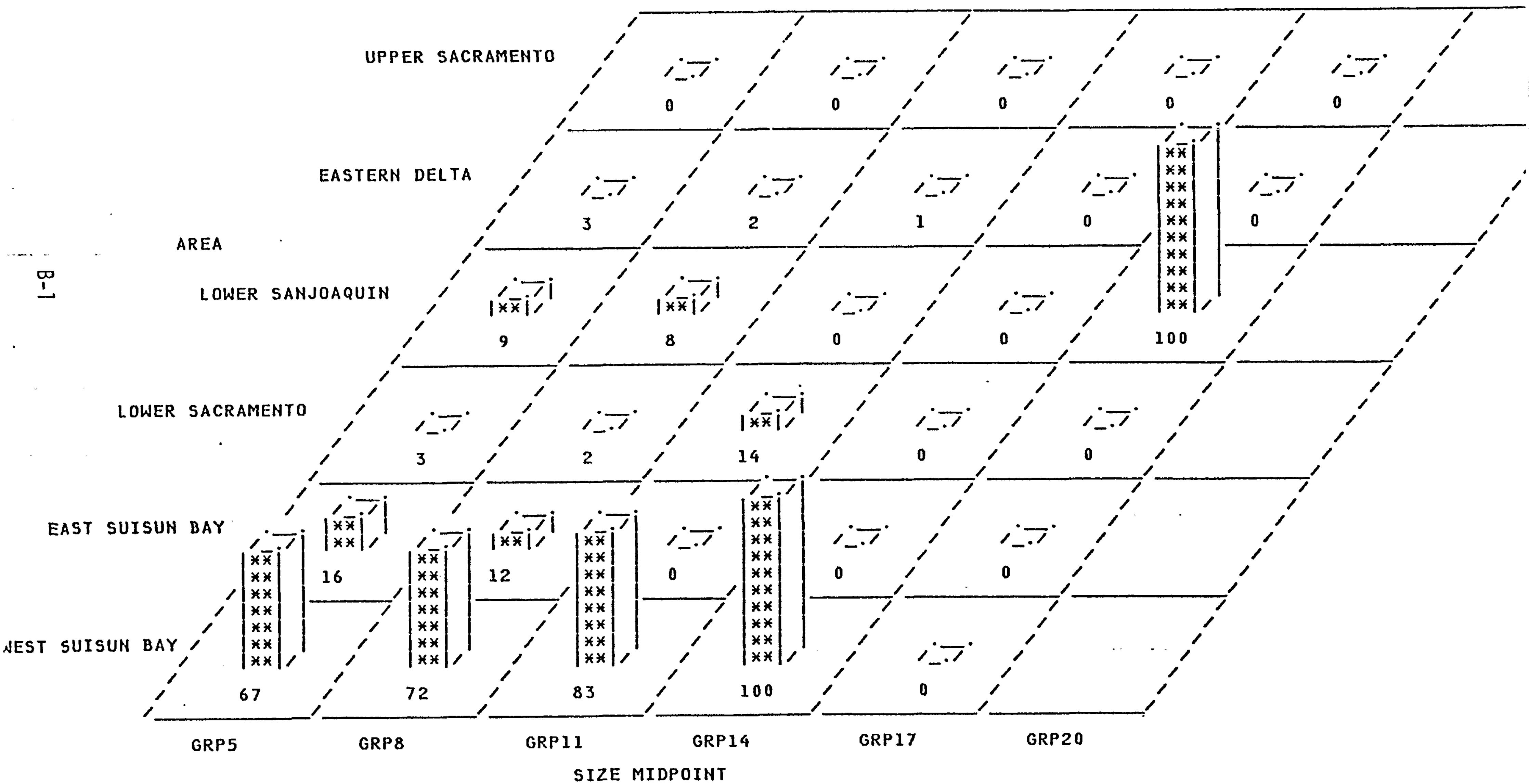


MEAN PERCENT OF STRIPED BASS SIZES 3-20 MM IN DELTA,
CDFG EGG AND LARVAL SURVEY, 1967-1977
YR=67

BLOCK CHART OF PERCENT



B-1

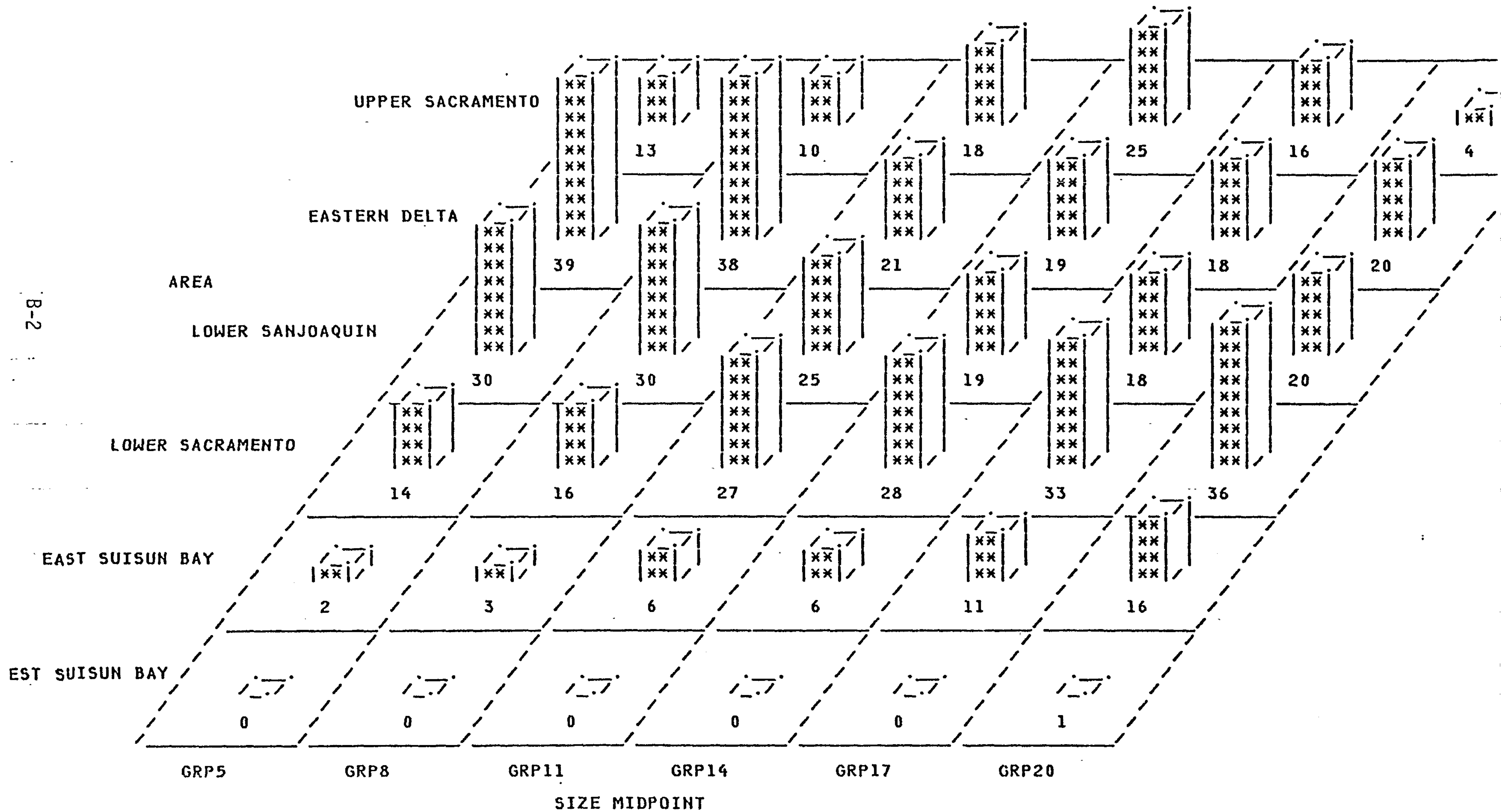
D—019817

D-019817

D-019818

MEAN PERCENT OF STRIPED BASS SIZES 3-20 MM IN DELTA,
CDFG EGG AND LARVAL SURVEY, 1967-1977
YR=68

BLOCK CHART OF PERCENT



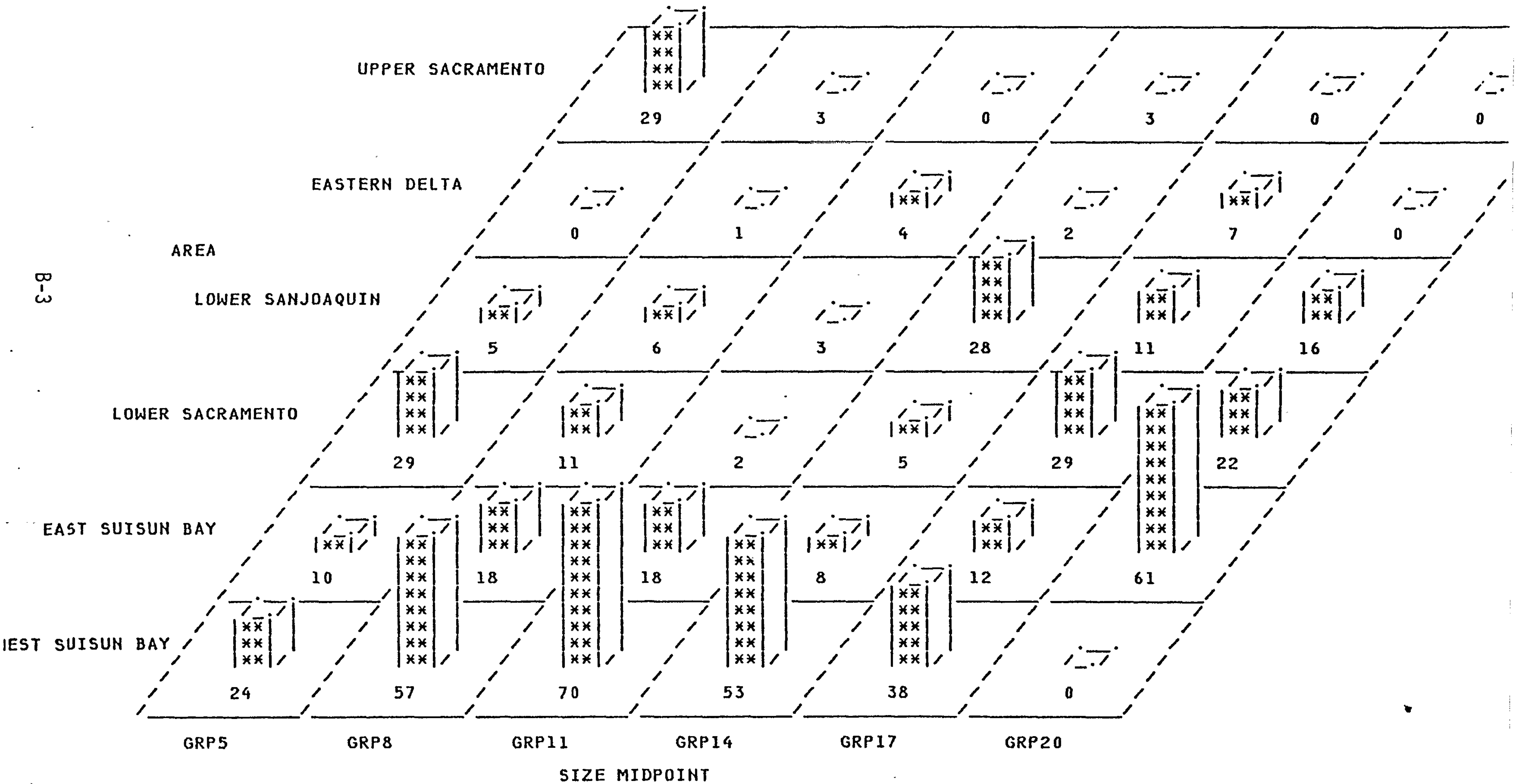
B-2

D-019818

D-019819

MEAN PERCENT OF STRIPED BASS SIZES 3-20 MM IN DELTA,
CDFG EGG AND LARVAL SURVEY, 1967-1977
YR=69

BLOCK CHART OF PERCENT

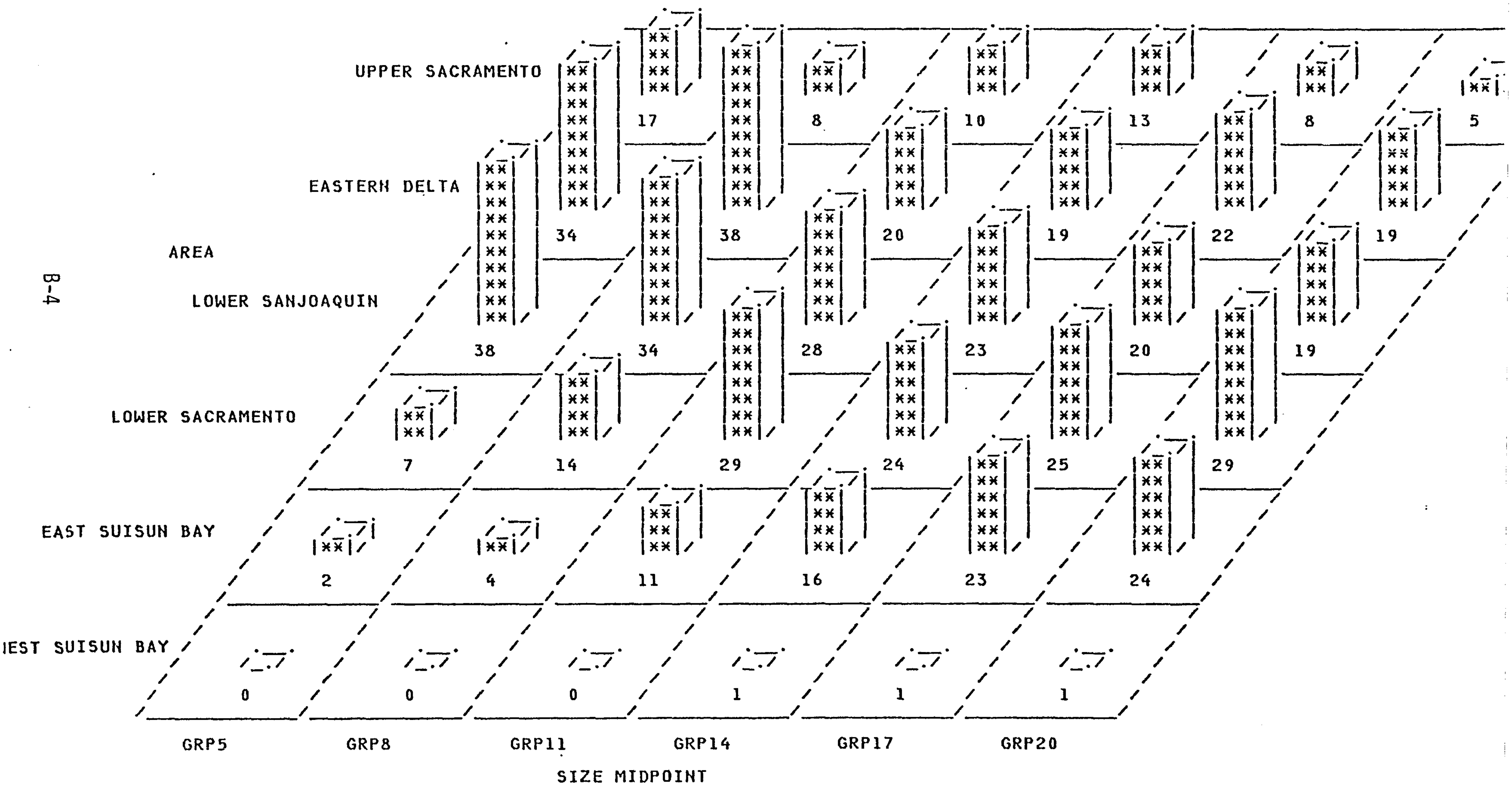


B-3

D-019819

MEAN PERCENT OF STRIPED BASS SIZES 3-20 MM IN DELTA,
CDFG EGG AND LARVAL SURVEY, 1967-1977
YR=70

BLOCK CHART OF PERCENT



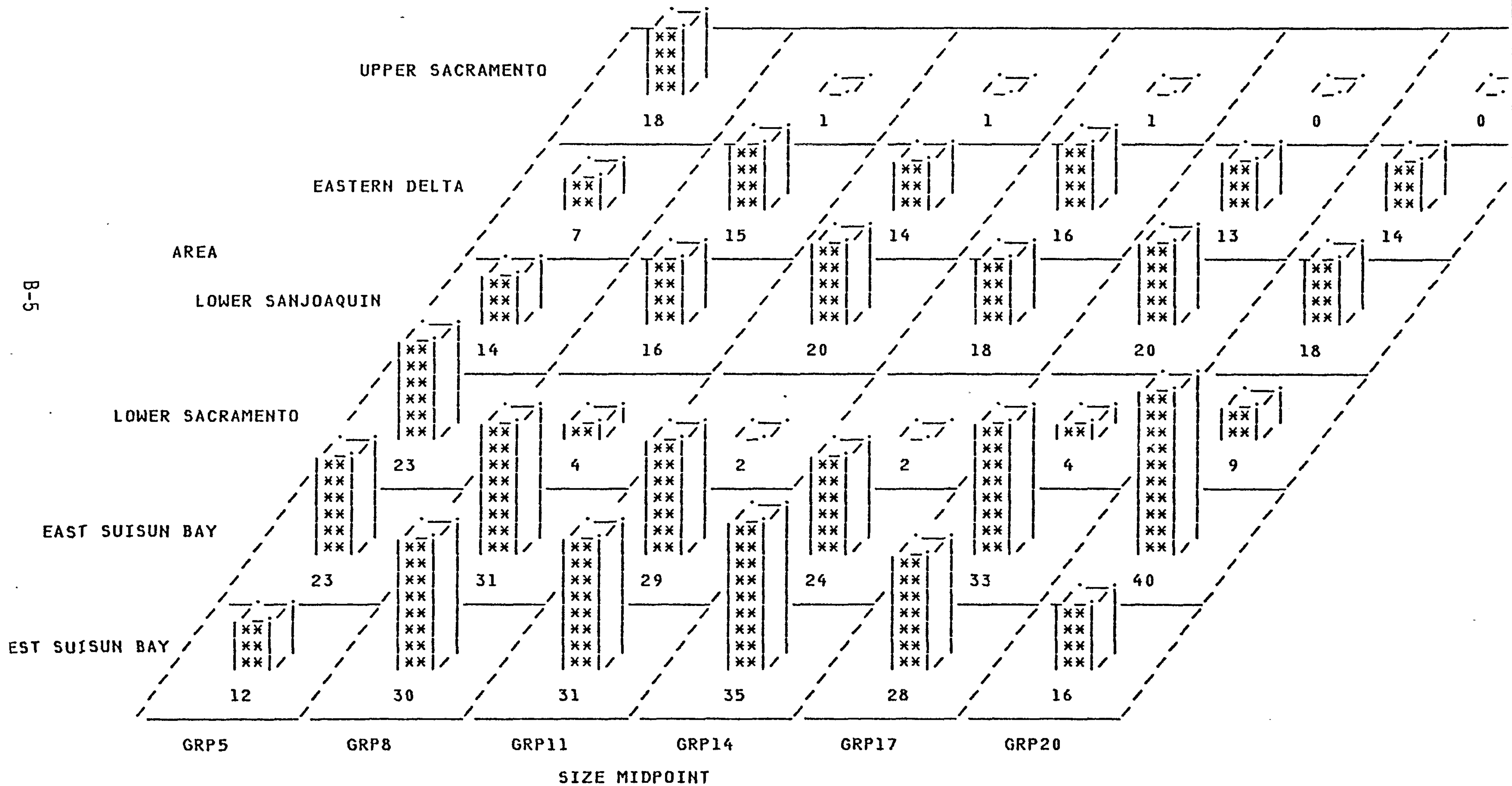
B-4

D-019820

D—019820

MEAN PERCENT OF STRIPED BASS SIZES 3-20 MM IN DELTA,
CDFG EGG AND LARVAL SURVEY, 1967-1977
YR=71

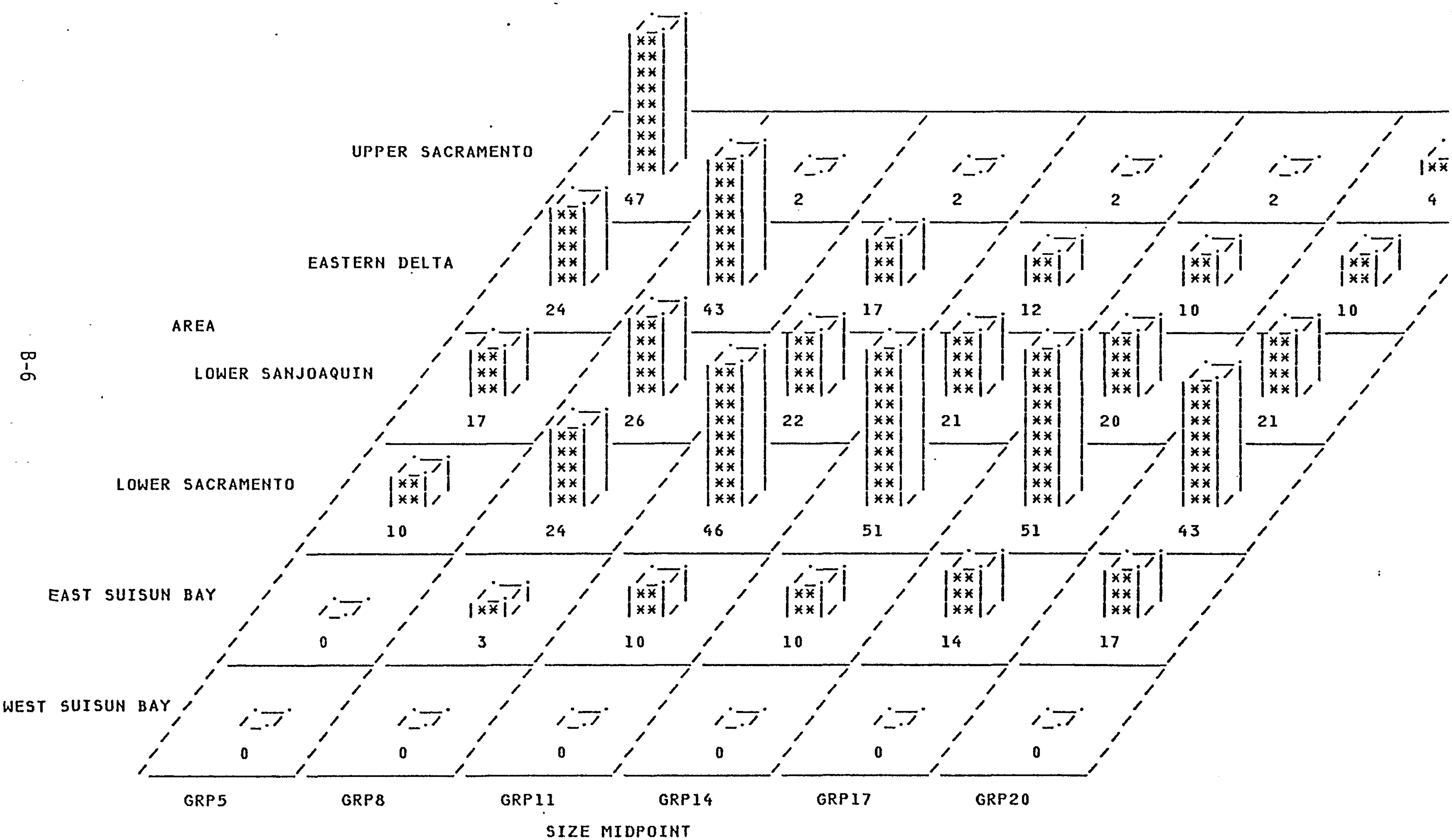
BLOCK CHART OF PERCENT



D-019821

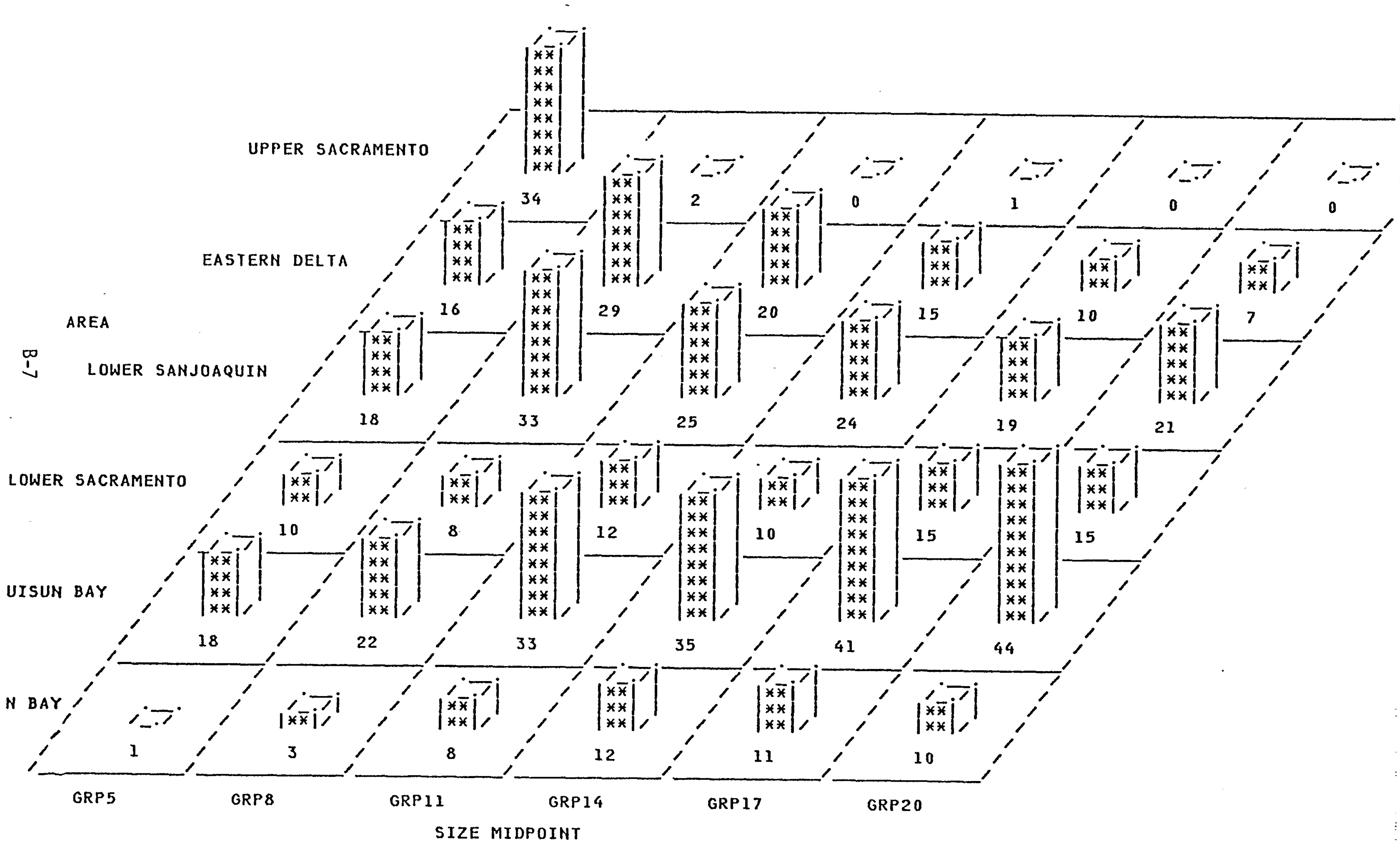
MEAN PERCENT OF STRIPED BASS SIZES 3-20 MM IN DELTA,
CDFG EGG AND LARVAL SURVEY, 1967-1977
YR=72

BLOCK CHART OF PERCENT



MEAN PERCENT OF STRIPED BASS SIZES 3-20 MM IN DELTA,
CDFG EGG AND LARVAL SURVEY, 1967-1977
YR=73

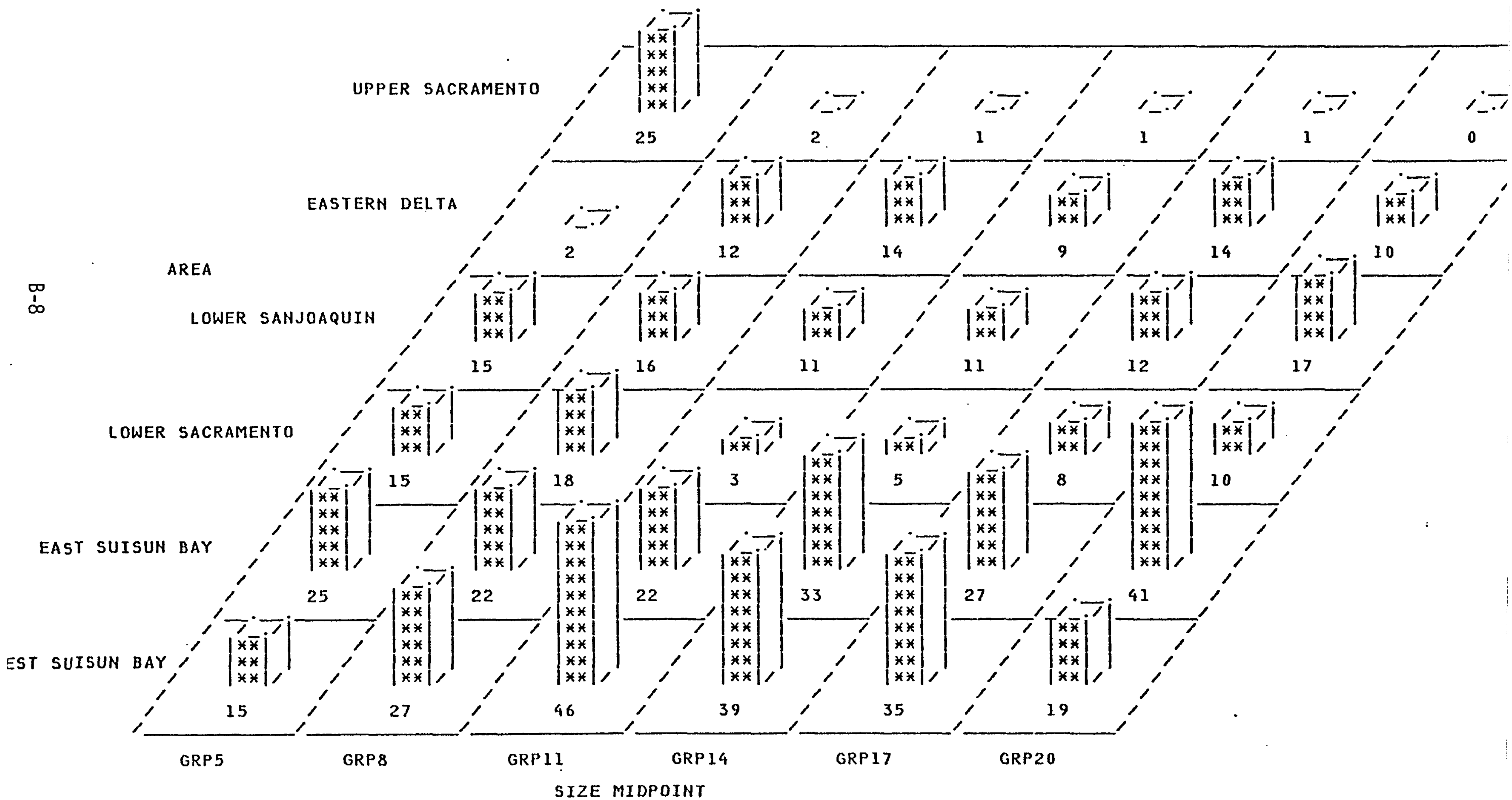
BLOCK CHART OF PERCENT



D-019823

MEAN PERCENT OF STRIPED BASS SIZES 3-20 MM IN DELTA,
CDFG EGG AND LARVAL SURVEY, 1967-1977
YR=75

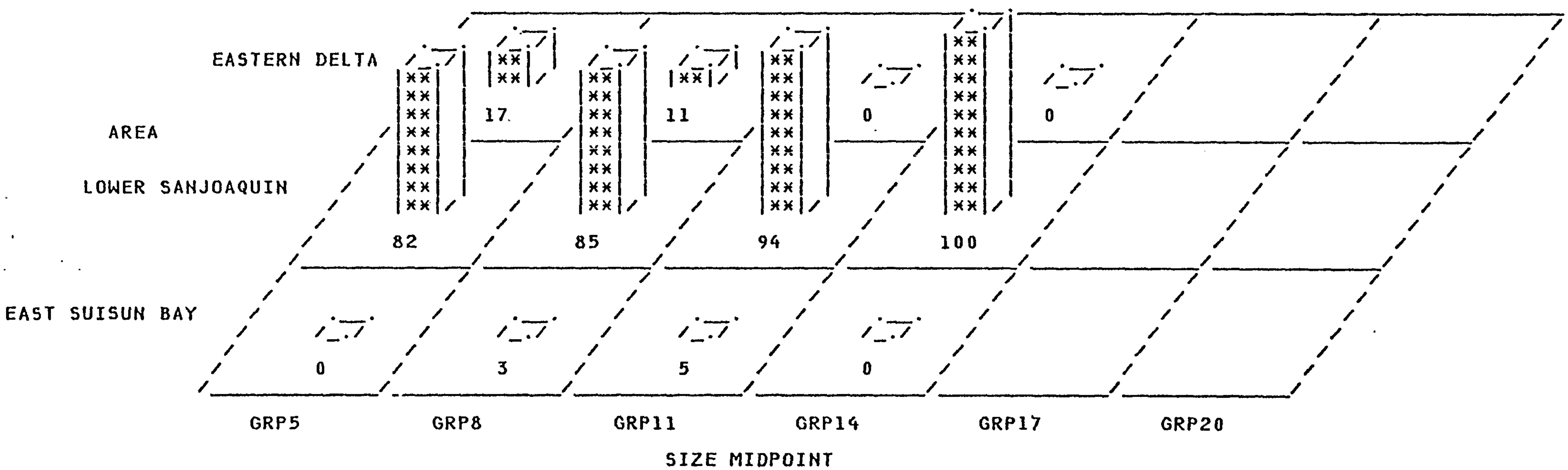
BLOCK CHART OF PERCENT



D-019824

MEAN PERCENT OF STRIPED BASS SIZES 3-20 MM IN DELTA,
CDFG EGG AND LARVAL SURVEY, 1967-1977
YR=76

BLOCK CHART OF PERCENT

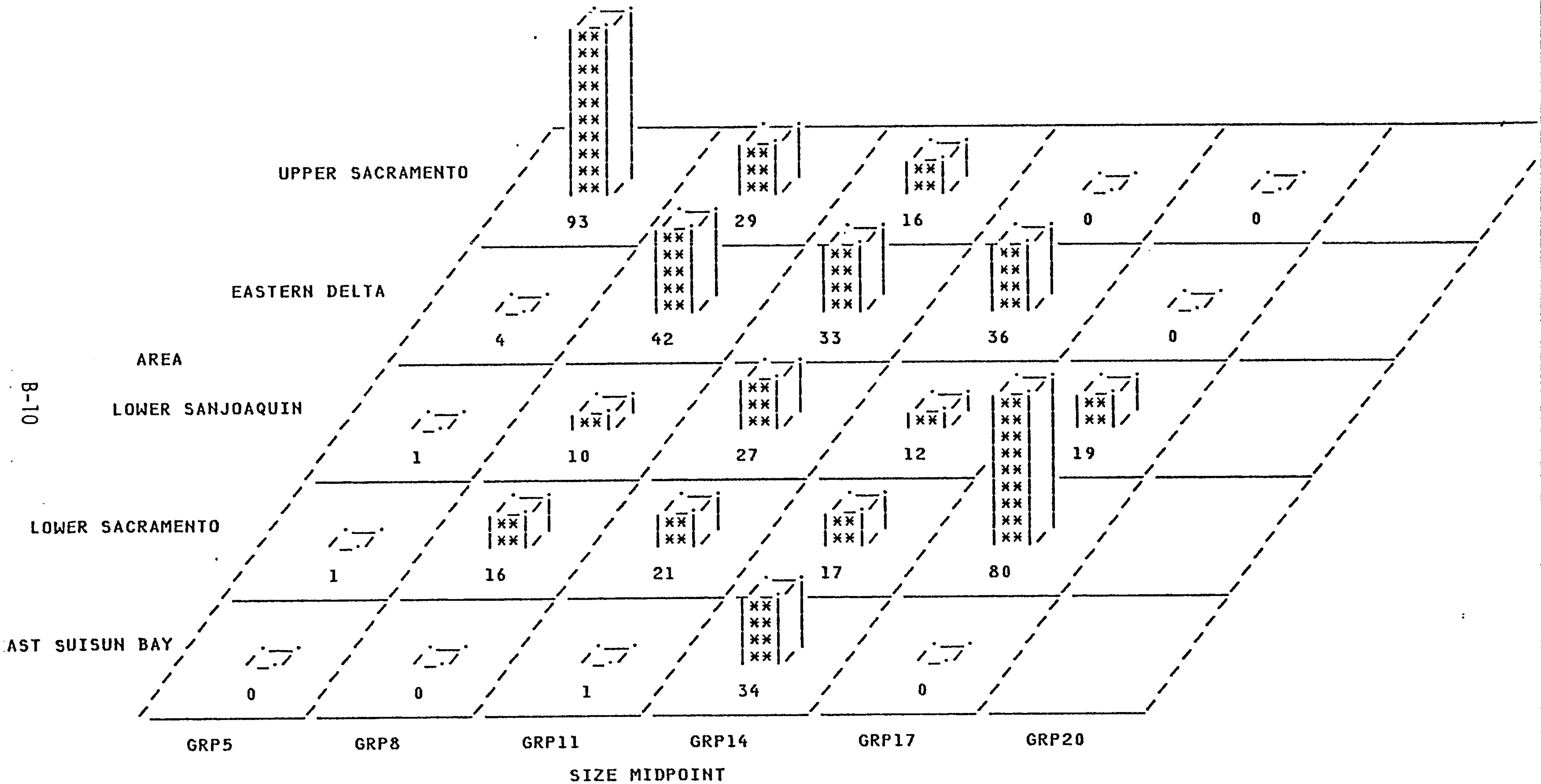


D-019825

D-019825

MEAN PERCENT OF STRIPED BASS SIZES 3-20 MM IN DELTA,
CDFG EGG AND LARVAL SURVEY, 1967-1977
YR=77

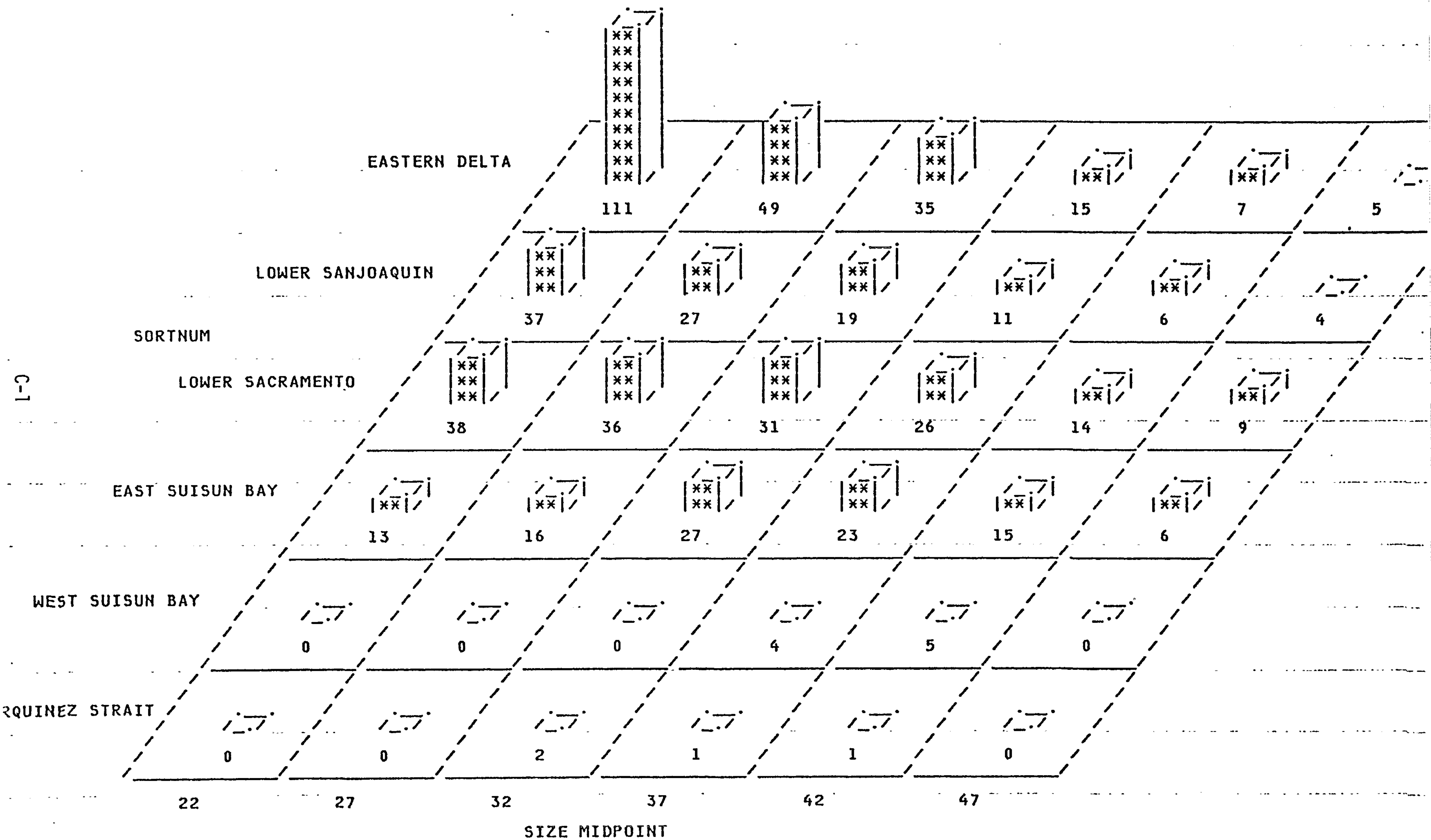
BLOCK CHART OF PERCENT



D-019826

YR=61

BLOCK CHART OF ABUND



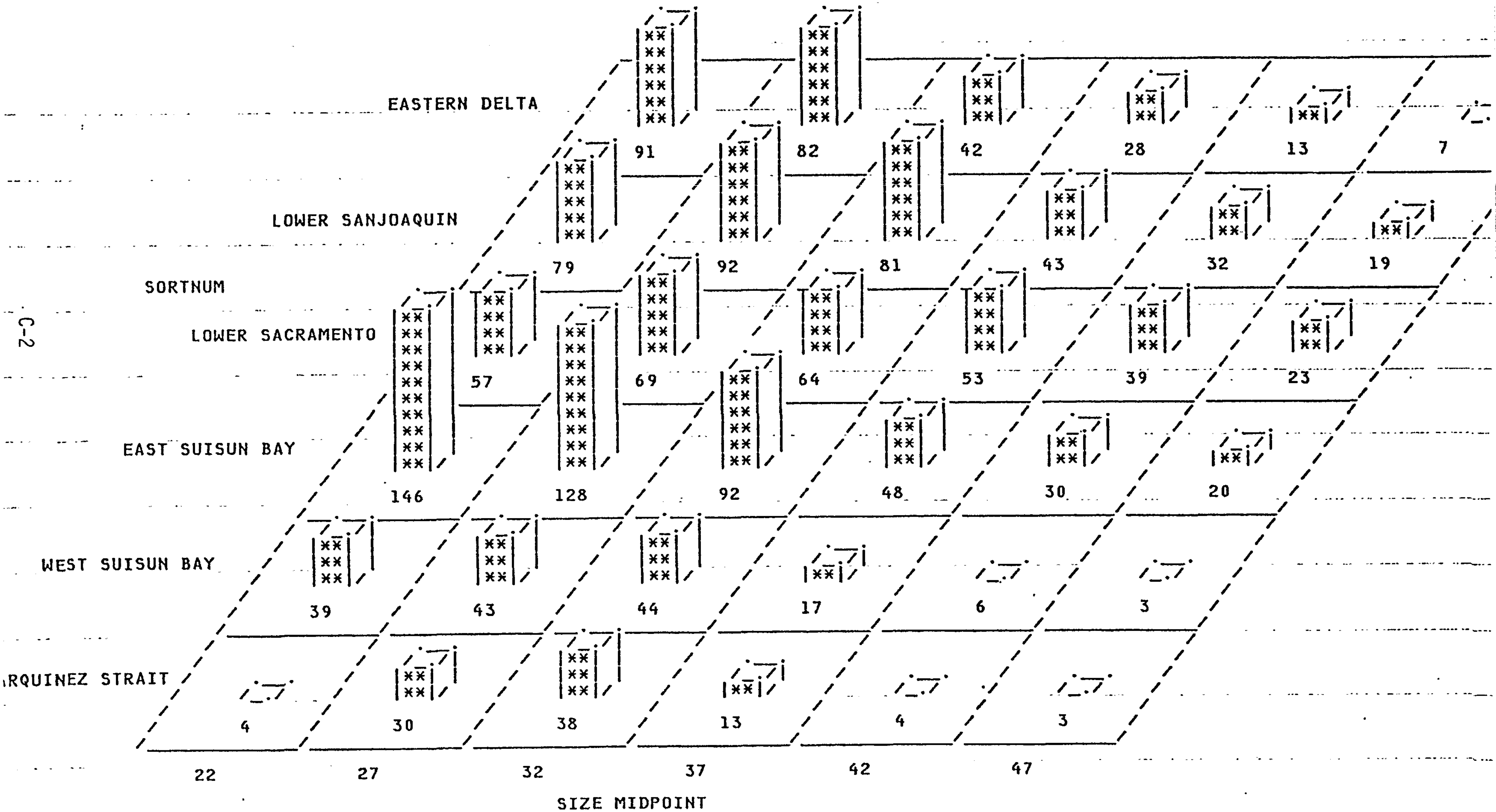
C-1

D-019827

D-019827

YR=62

BLOCK CHART OF ABUND

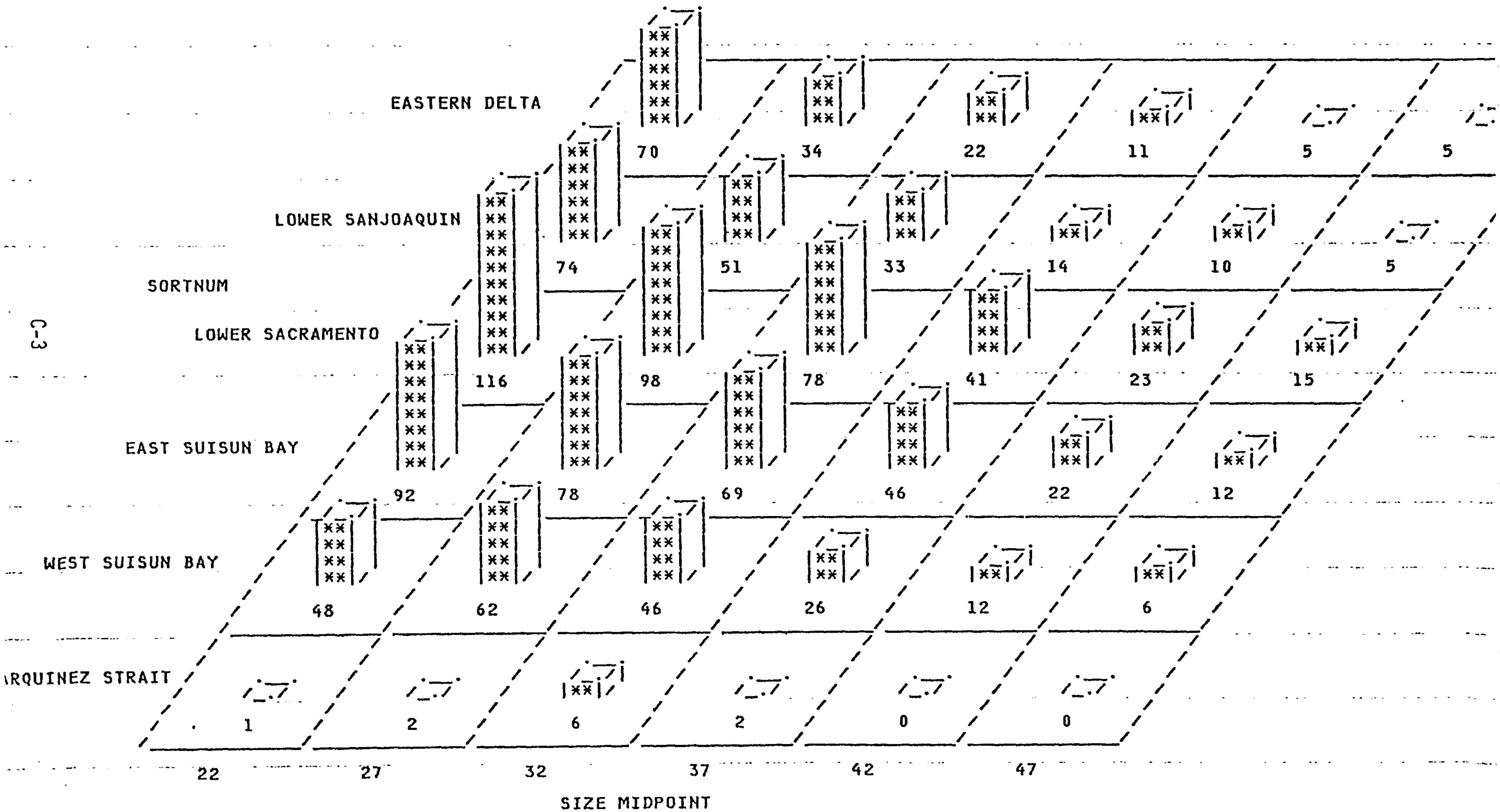


C-2

D-019828

YR=63

BLOCK CHART OF ABUND



C-3

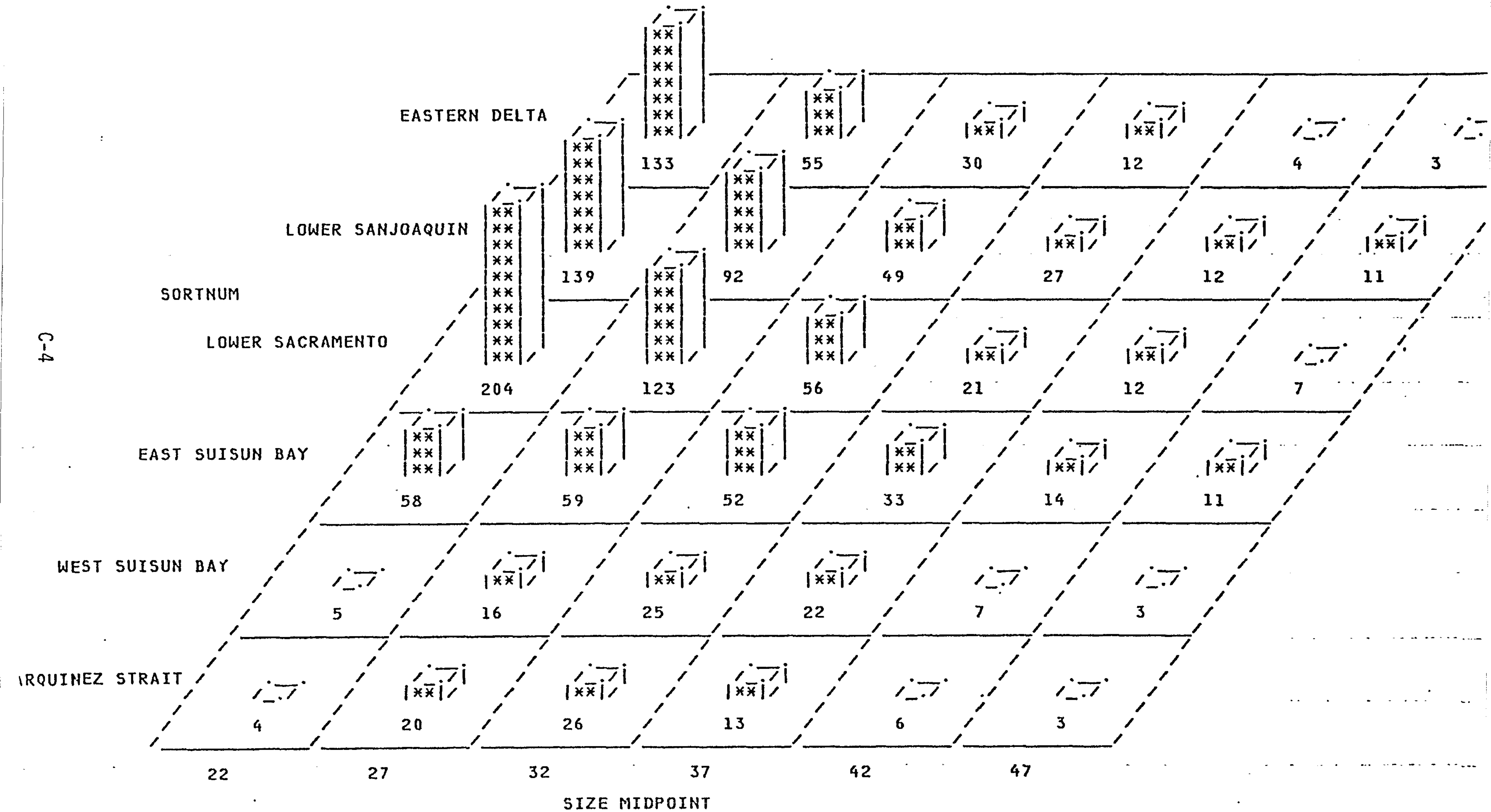
D-019829

D-019829

D-019830

YR=64

BLOCK CHART OF ABUND

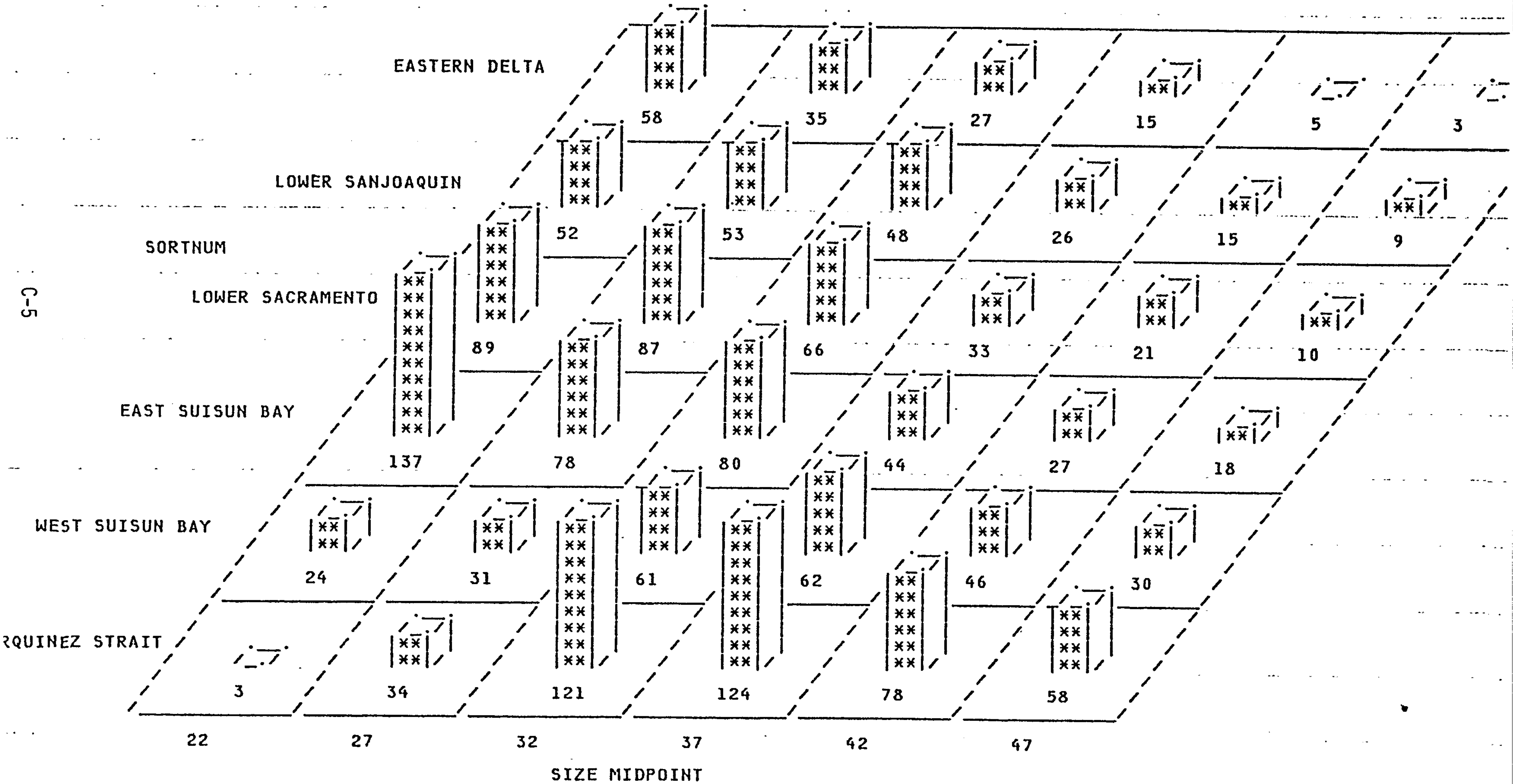


C-4

D—019830

YR=65

BLOCK CHART OF ABUND



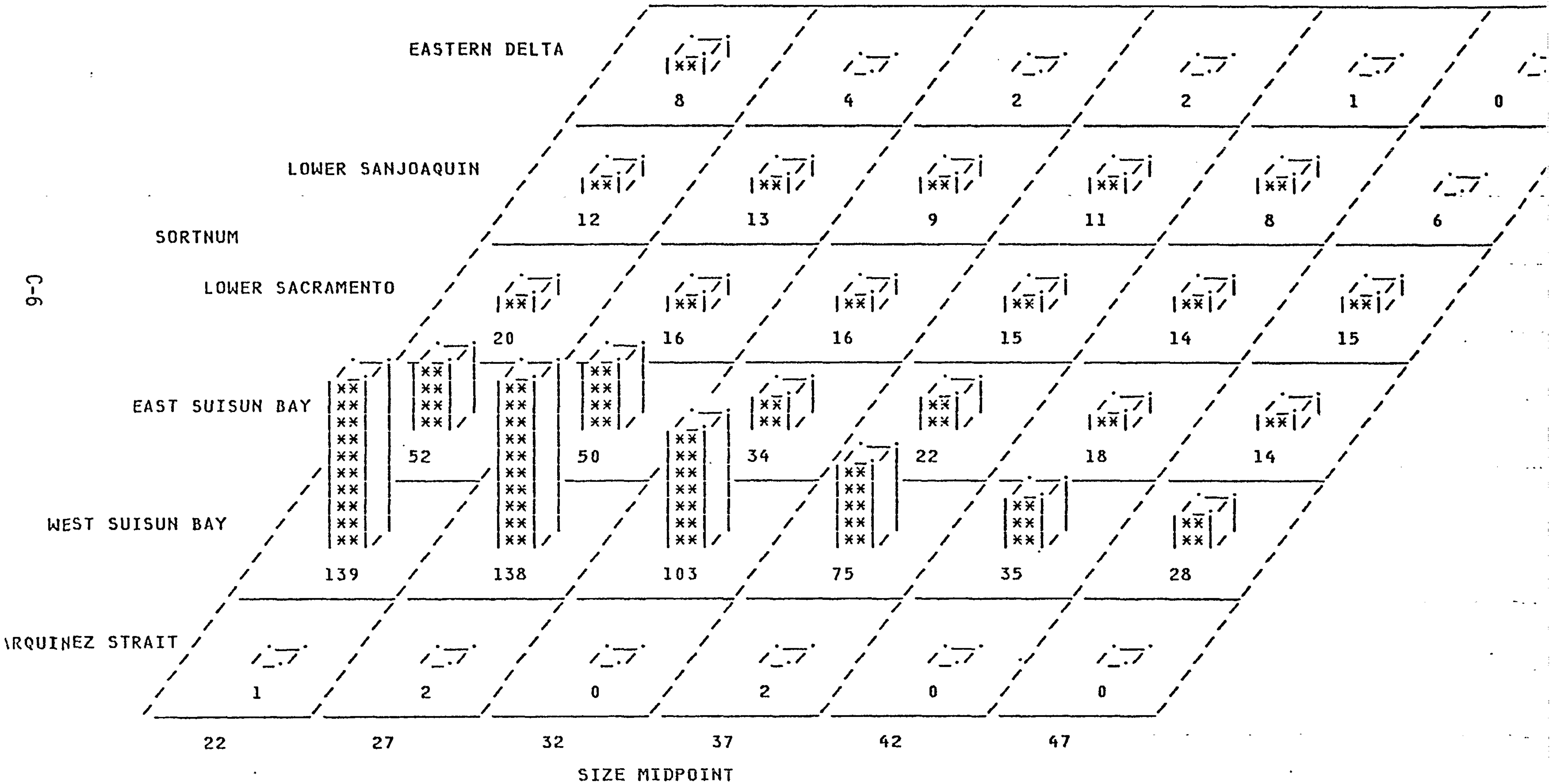
C-5

D-019831

D-019831

YR=67

BLOCK CHART OF ABUND



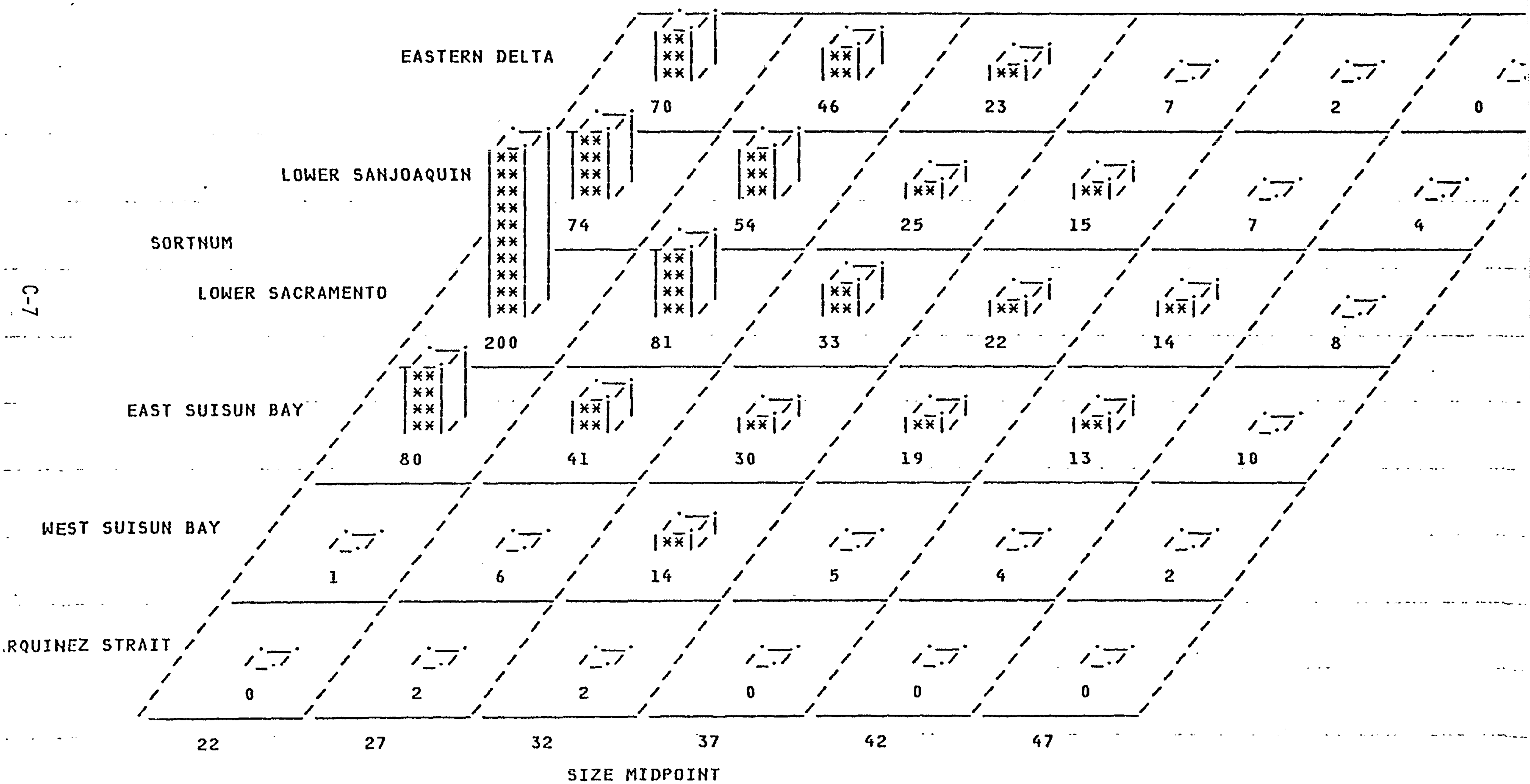
C-6

D-019832

D-019832

YR=68

BLOCK CHART OF ABUND



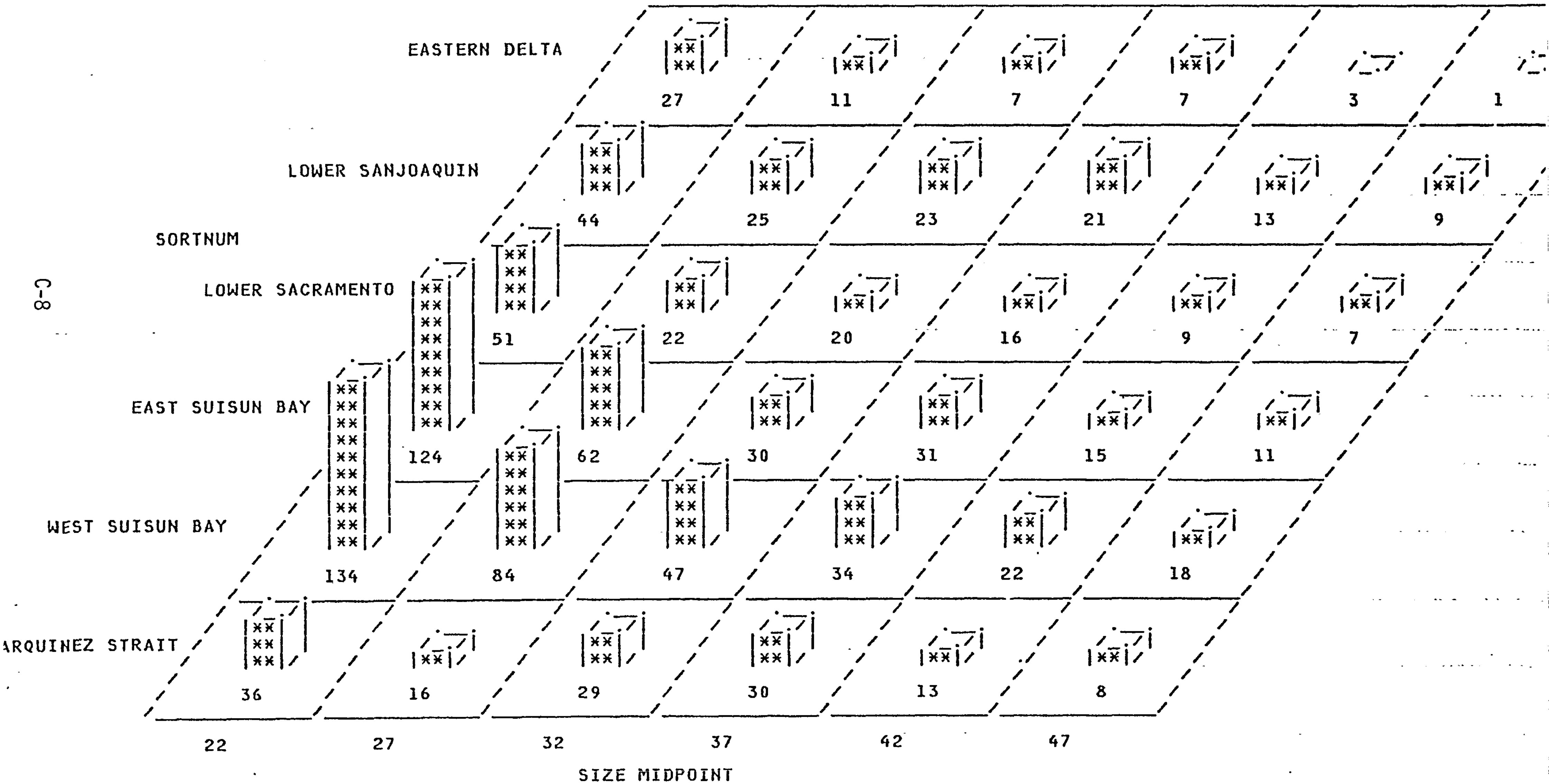
C-7

D-019833

D-019833

YR=69

BLOCK CHART OF ABUND

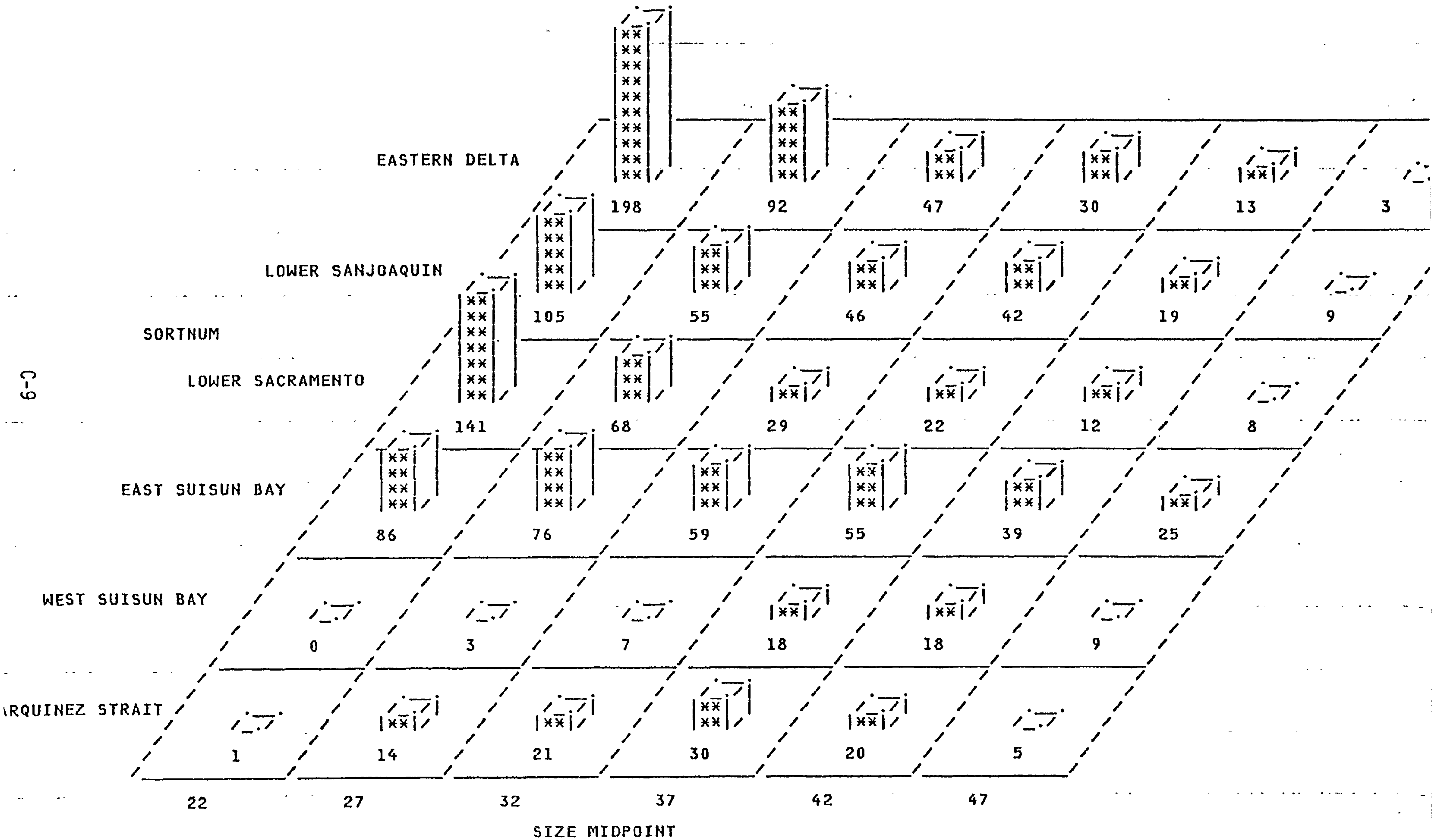


C-8

D—019834

YR=70

BLOCK CHART OF ABUND



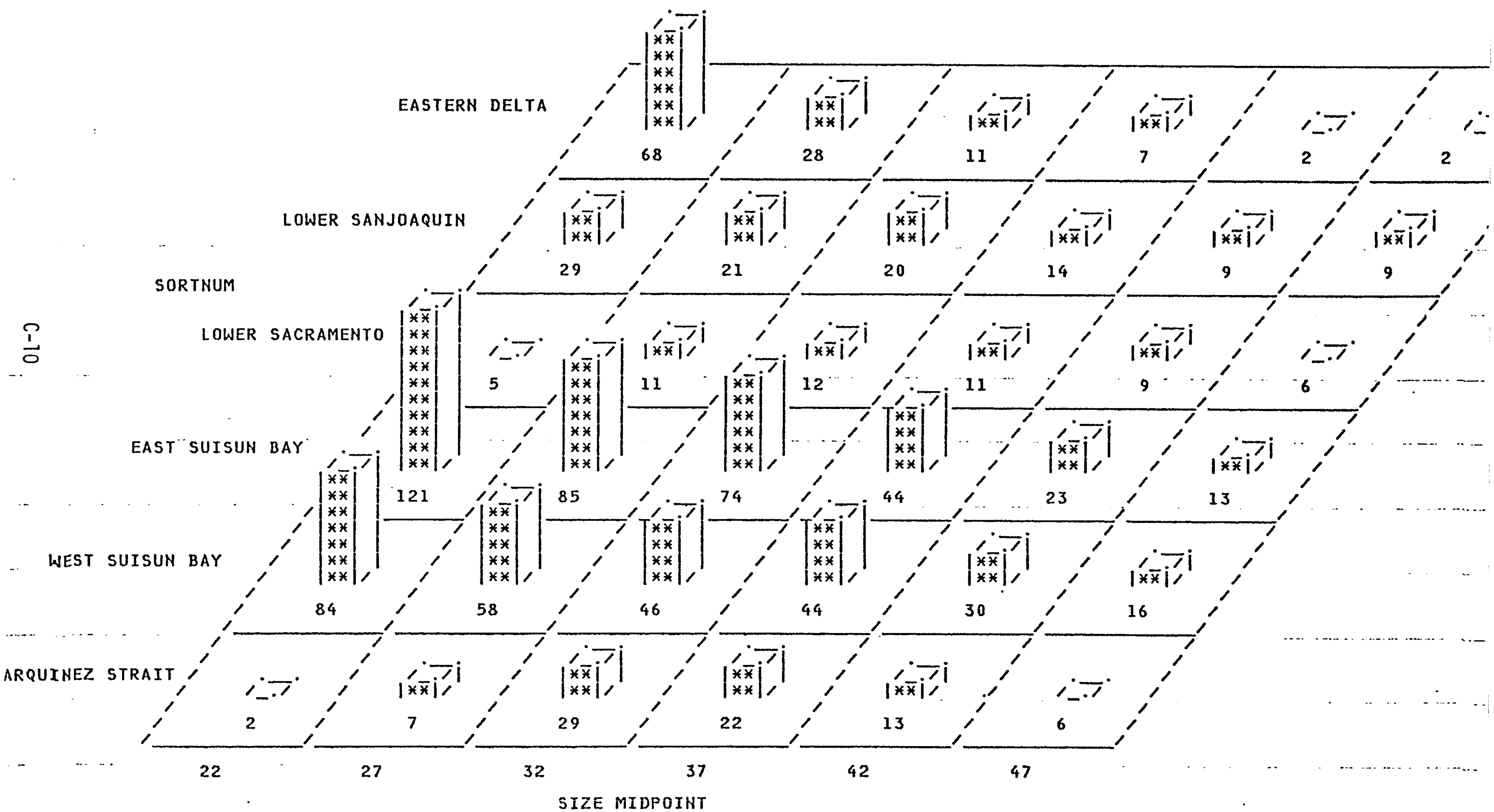
C-9

D-019835

D-019835

YR=71

BLOCK CHART OF ABUND



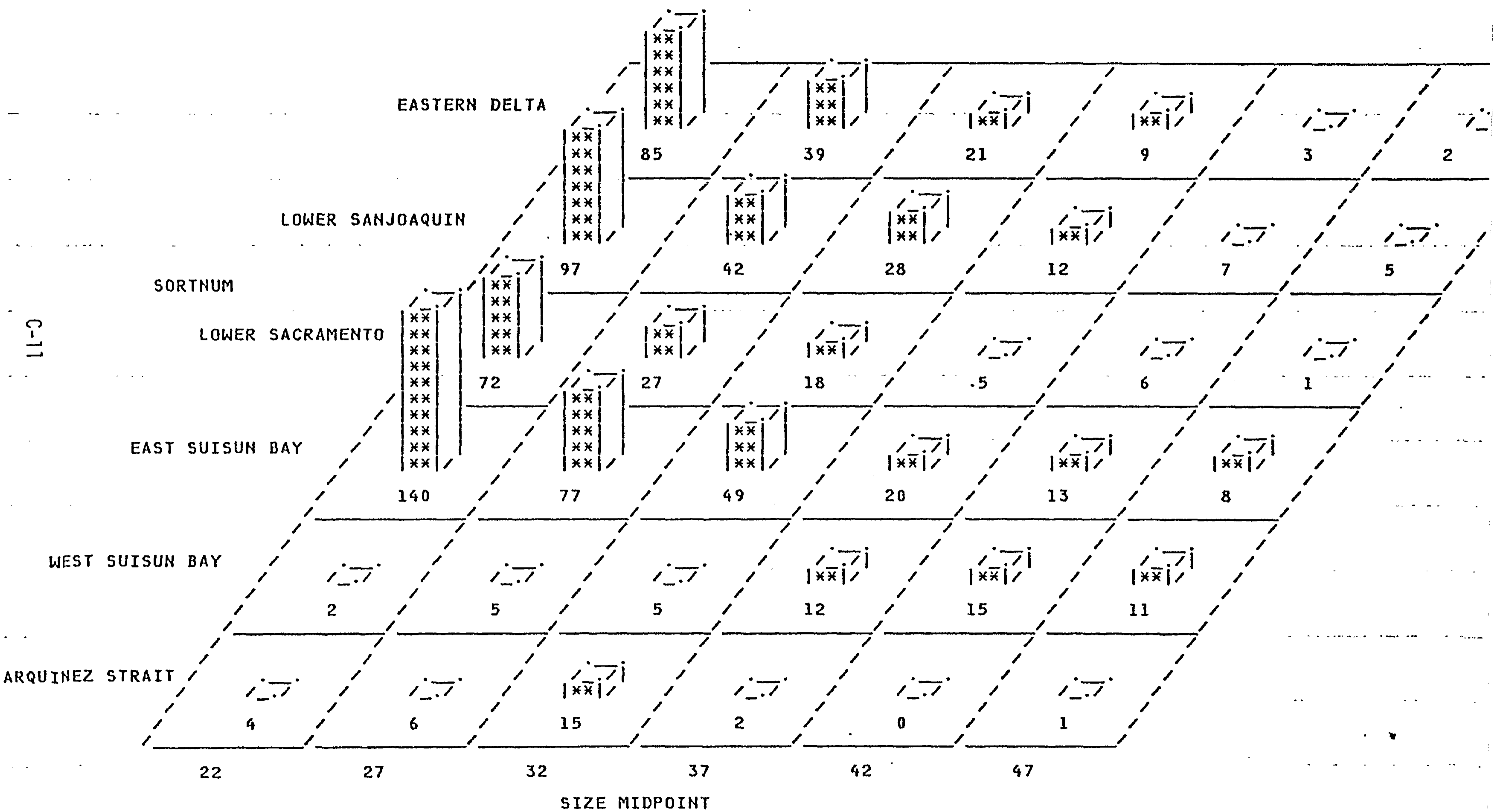
C-10

D-019836

D—019836

YR=72

BLOCK CHART OF ABUND



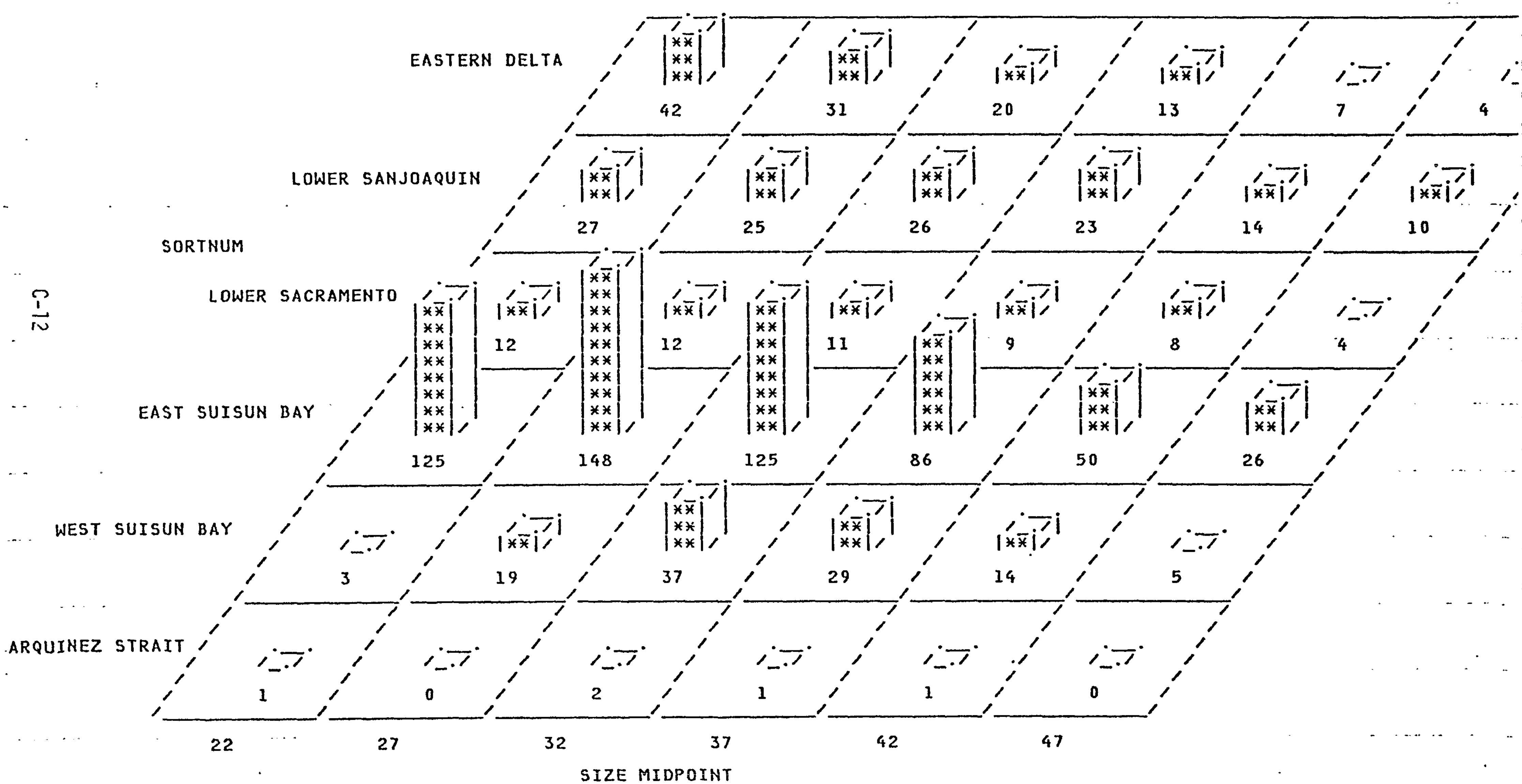
C-11

D-019837

D-019837

YR=73

BLOCK CHART OF ABUND



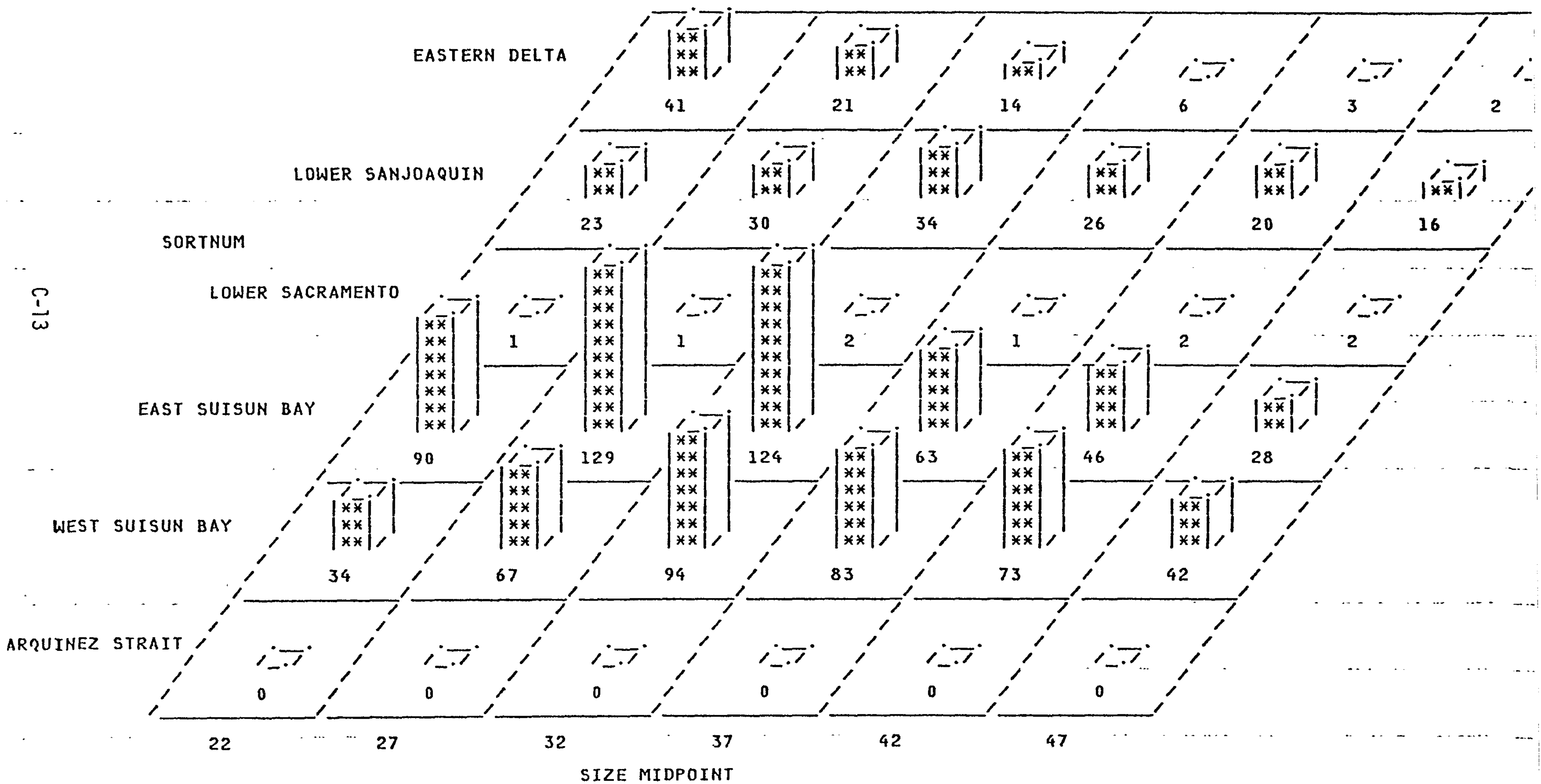
C-12

D-019838

D-019838

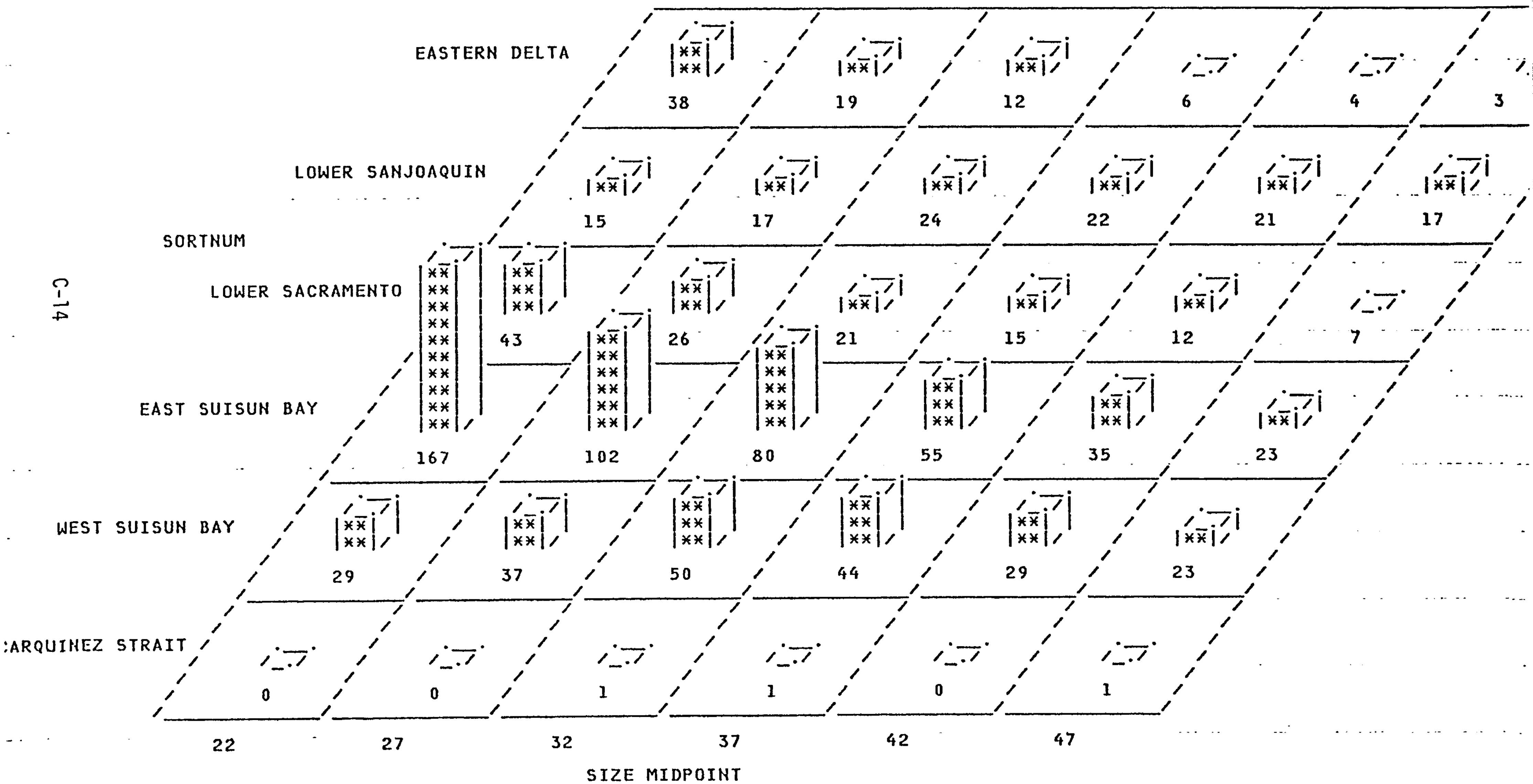
YR=74

BLOCK CHART OF ABUND



YR=75

BLOCK CHART OF ABUND



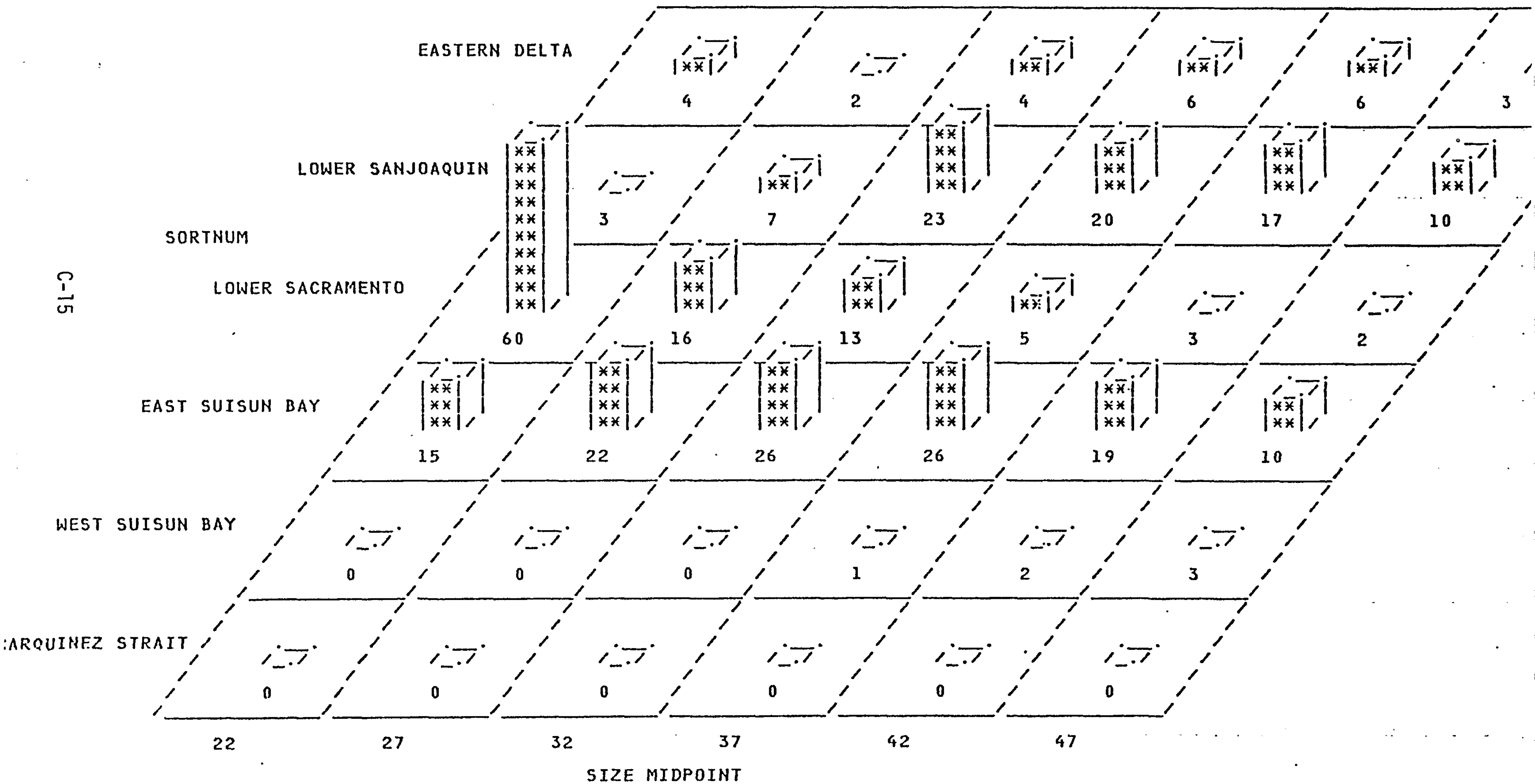
C-14

D-019840

D-019840

YR=76

BLOCK CHART OF ABUND



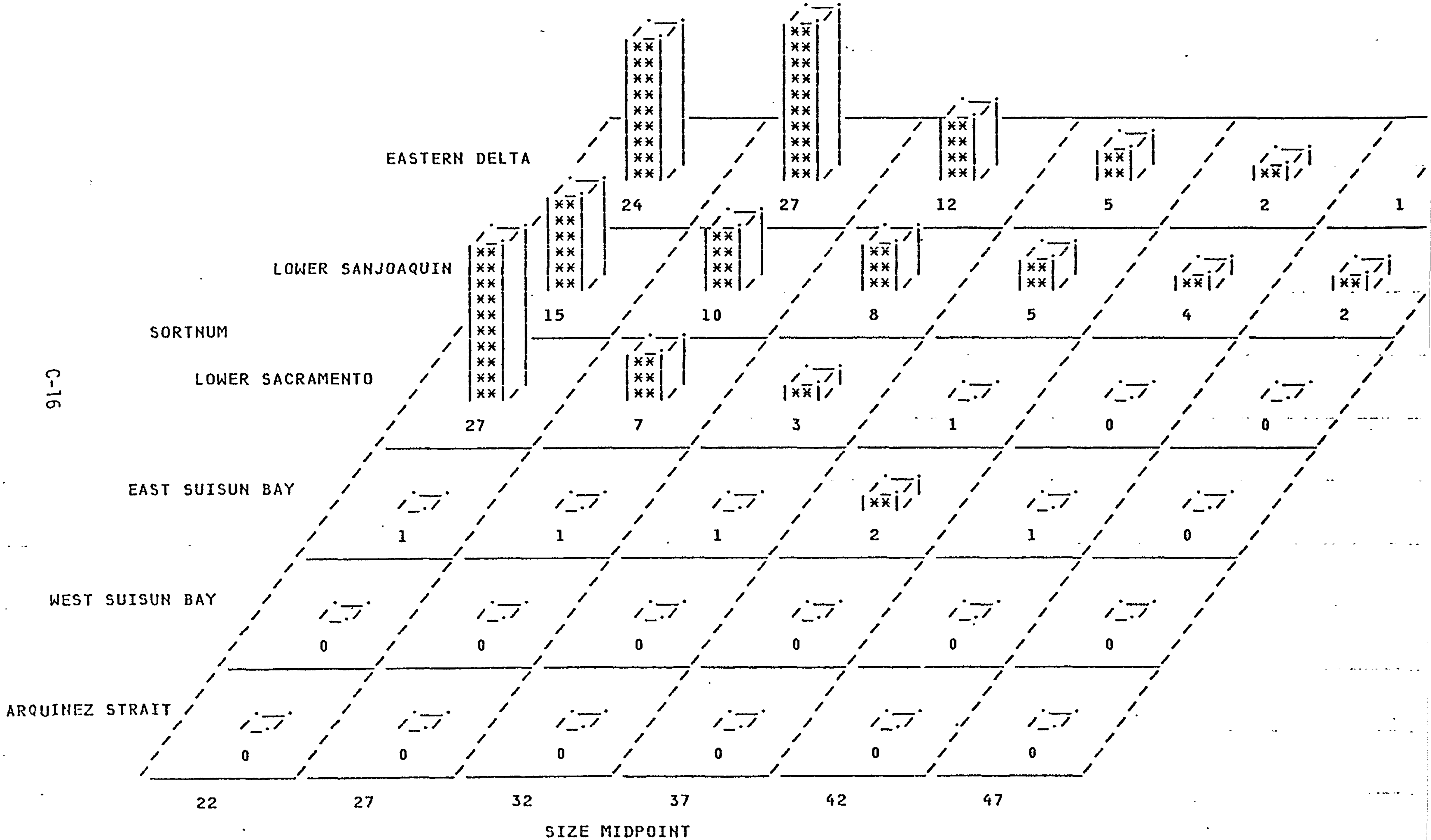
C-15

D-019841

D-019841

YR=77

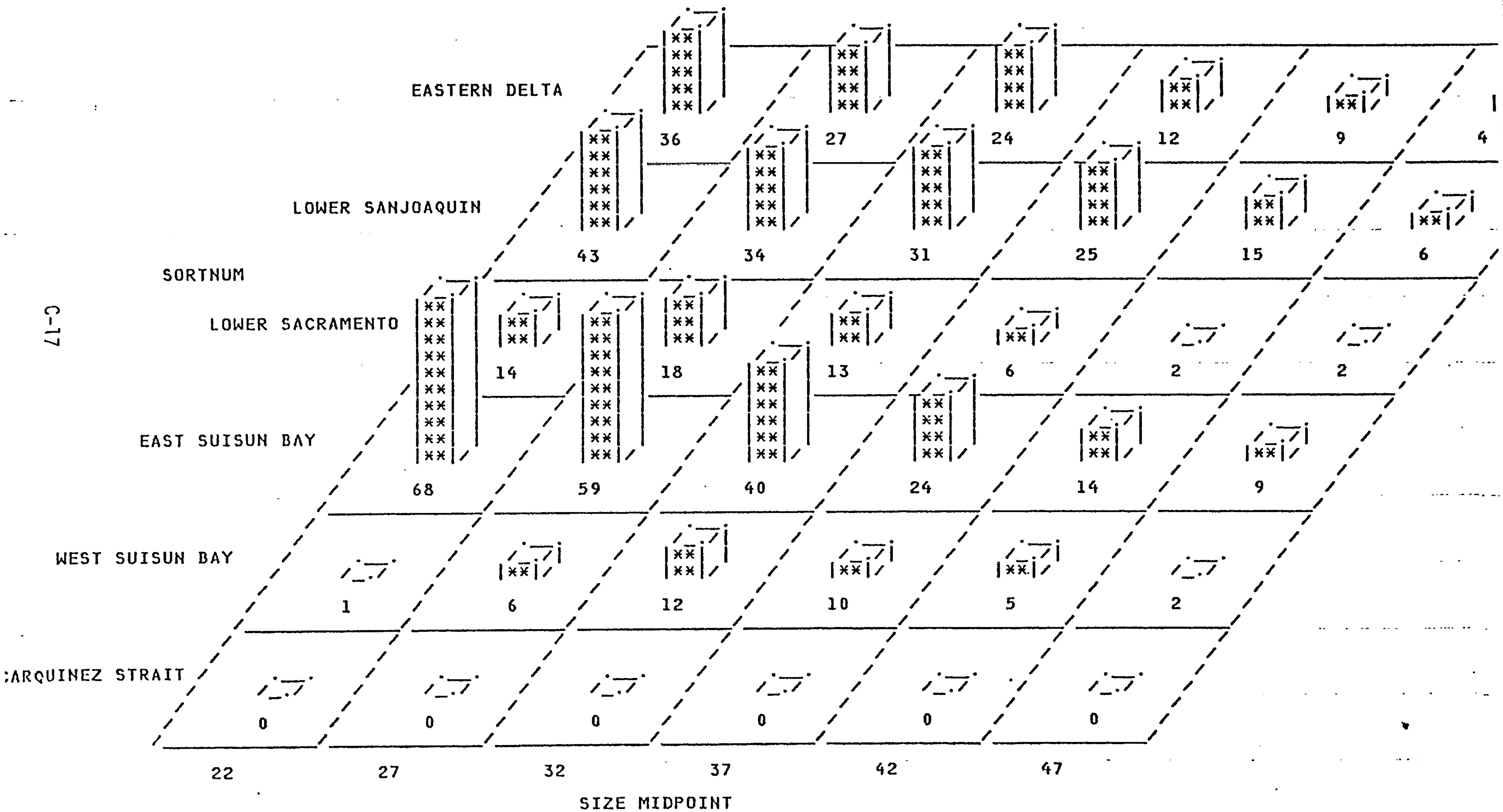
BLOCK CHART OF ABUND



D-019842

YR=78

BLOCK CHART OF ABUND



D-019843